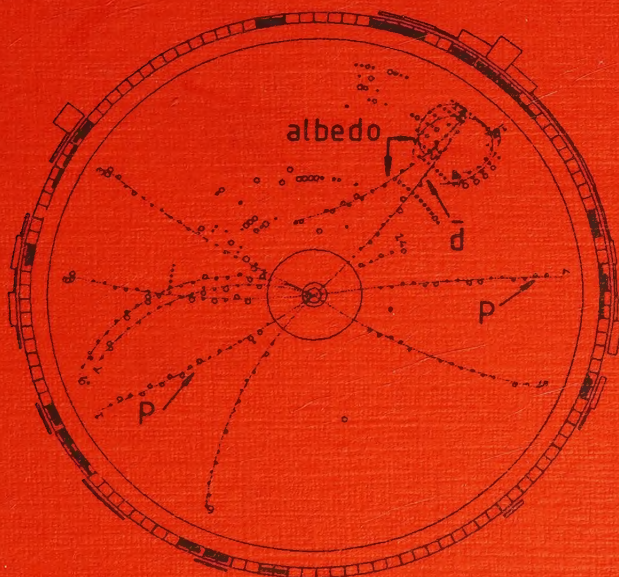


A STUDY OF PARTICLES PRODUCED IN e^+e^- ANNIHILATION AT A
CENTER-OF-MASS ENERGY OF AROUND 10 GeV, USING IONIZATION LOSS
MEASUREMENTS.

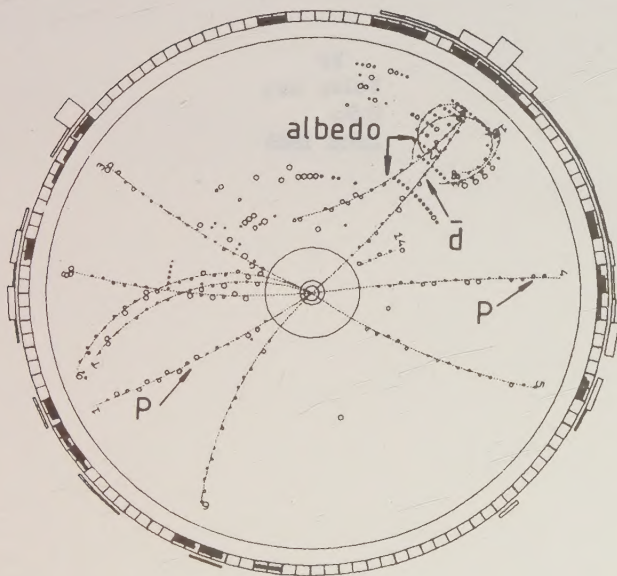
Yukio Oku



LUND 1985

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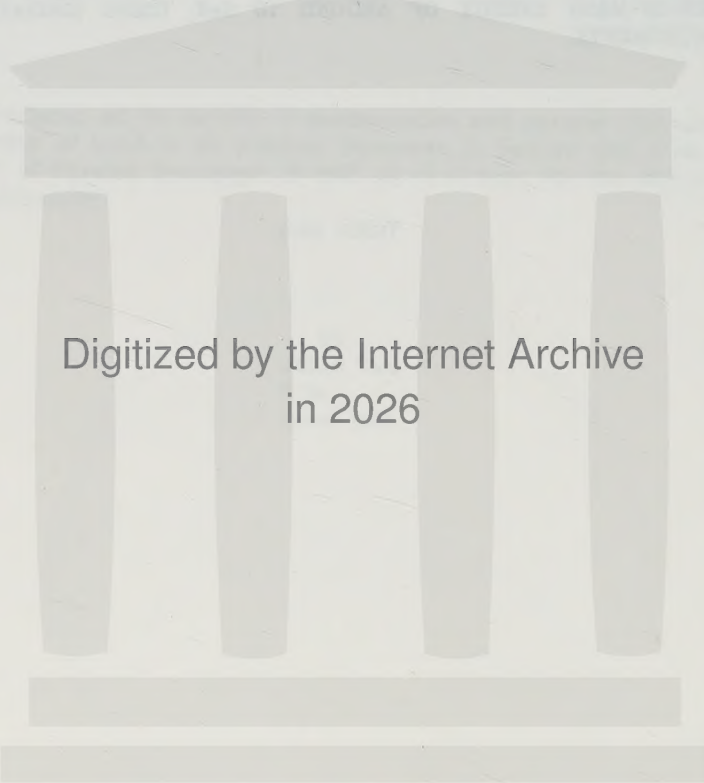
By due permission of the faculty of mathematics and natural sciences of
the University of Lund to be publicly discussed in lecture hall B of the
department of Physics, December 16 1985, at 10.15 a.m., for the degree of
doctor of philosophy.

by
Yukio Cku
B.Sc.
Lund 1985

A STUDY OF PARTICLES PRODUCED IN e^+e^- ANNIHILATION AT A
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Yukio Oku

LUND 1985



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М. ДАНИЛОВУ

ABSTRACT

Using the particle identification system of the ARGUS detector at the DORIS II storage ring, operating at a centre of mass energy of around 10 GeV, a search has been made for particles with unexpected ionization produced in e^+e^- . The production of antideuterons has been observed for the first time in e^+e^- annihilation. No other unexpected ionizing particles were found in 84.5 pb^{-1} of collected data. Upper limits are established for the production cross section of fractionally charged particles with masses up to $4 \text{ GeV}/c^2$, improving on previously obtained limits.

Also the observation and analysis of D^* , F and F^* mesons relied to large extent on the particle identification system.

ABSTRAKT

ARGUS detektorn vid e^+e^- lagringsringen DORIS II har utnyttjats för att med hjälp av dess partikelidentifieringssystem leta efter partiklar med oväntad jonisering. Produktion av antideuteroner har observerats för första gången i e^+e^- annihilation. Inga andra partiklar med oväntad jonisering hittades i en datamängd motsvarande 84.5 pb^{-1} . Övre gränser för produktionsträffytan för partiklar med icke heltalsladdning laddning upp till $4 \text{ GeV}/c^2$ massa har fastställts och är en förbättring av tidigare resultat.

Tillämpningen av partikelidentifieringssystemet spelade en avgörande roll också vid observationen och analysen av D^* , F och F^* mesonerna.

ACKNOWLEDGEMENT

This thesis was possible because of the successful construction and operation of the ARGUS detector. I would like to thank all the members of the collaboration, and especially I would like to thank Prof. R. Childers for advice concerning the magnetic field parametrization, Prof. P. Patel and Dr. Yu. Zaitsev for the help with the free quark search, and Dr. D. MacFarlane for the help with English.

I would like to give my best thank to Dr. M. Danilov. I can not imagine the existence of this thesis without his advice.

Danksagung

Diese Arbeit entstand im Rahmen der ARGUS Kollaboration. Allen Mitgliedern der Kollaboration möchte ich für ihr Hilfe und Unterstützung bei der Anfertigung der Arbeit danken.

Mein besonderer Dank gilt, Herrn Dr. W. Schmidt-Parzefall, Herrn Dr. Prof. D. Wegener, Herrn Dr. H. Schröder, Herrn Dr. H. Hasemann, Herrn Dr. H. Albrecht, Herrn Dr. J. Spengler, Herrn S. Weseler, und Herrn W. Reinsch.

Tackord

Jag skulle vilja tacka alla på institutionen för fysik vid Lunds Universitet, speciellt skulle jag vilja tacka följande personer: Prof. B. Andersson, Dr. P. Böckmann, Prof. G. von Dardel, Dr. P. Ekström, Dr. G. Jarlskog, Dr. L. Jönsson, Dr. B. Lörstad, Dr. A. Nilsson och Dr. T. Sjöstrand.

Jag skulle också vilja tacka herr R. Bexander i Stockholm.

Yukio Oku
01.10.1985 at DESY

CONTENTS

1.0 INTRODUCTION	1
2.0 GENERAL DESCRIPTION OF THE EXPERIMENT	7
2.1 DORIS II storage ring	7
2.2 Luminosity	8
2.3 The ARGUS detector	12
2.3.1 The coordinate system	14
2.3.2 The mini- β quadrupoles, the compensation coils and the ARGUS magnet.	15
2.3.3 The drift chamber	22
2.3.4 The Time Of Flight (TOF) system	46
2.3.5 The Shower counter system	49
2.3.6 The Muon chambers	50
2.4 Data	50
2.4.1 Trigger	50
2.4.2 Multihadron events	50
2.4.3 Two prong events	51
3.0 SEARCH FOR FRACTIONALLY CHARGED PARTICLES	52
3.1 The search	52
3.1.1 Data	52
3.1.2 The event selection	52
3.2 The result of the search	58
3.2.1 Selected events from multihadron data	58
3.2.2 Selected events from two prong data	63
3.3 Efficiencies	64
3.3.1 The efficiency in the upper region	64
3.3.2 The efficiency in the lower region	66
3.4 Final results	66
4.0 THE FIRST OBSERVATION OF ANTIDEUTERON PRODUCTION IN ELECTRON POSITRON ANNIHILATION	69
4.1 The search	69
4.2 Antideuteron candidates	69
4.2.1 The evidence	69
4.2.2 Examples	75
4.3 Results and discussion	78
4.3.1 Lorentz invariant cross section	78
4.3.2 Characteristics of the events with antideuteron	80
4.3.3 Baryon correlation	80
4.3.4 Discussions	81

5.0	THE APPLICATION OF THE DE/DX MEASUREMENTS TO THE CHARM PHYSICS	83
5.1	Production and decay of the charged D^* meson	83
5.2	Production and decay of the F meson	84
5.3	Evidence for F^* meson production	85
6.0	SUMMARY	88
	REFERENCES	89

LIST OF ILLUSTRATIONS

Figure 1.	The hexadecimet of the pseudoscalar mesons	5
Figure 2.	The electron-positron storage ring DORIS II	7
Figure 3.	Collision between bunches of particles	8
Figure 4.	The differential cross section	10
Figure 5.	The ARGUS detector as of 1984	13
Figure 6.	The ARGUS coordinate system	15
Figure 7.	The Mechanical mounting of probes	17
Figure 8.	The measuring grid	18
Figure 9.	The measured field value	19
Figure 10.	The magnetization	20
Figure 11.	The pattern of the potential wires as seen from the end plate	22
Figure 12.	Equipotentials of the drift chamber	24
Figure 13.	Drift chamber cross section parallel to the beam	25
Figure 14.	The space-time relation	28
Figure 15.	A typical multihadron event	29
Figure 16.	A measured χ^2 -probability distribution	31
Figure 17.	The energy loss distribution	33
Figure 18.	The truncated mean of the energy loss vs. momentum	34
Figure 19.	The dependence of the collected charge on the angle of the track	36
Figure 20.	dE/dx for 5 GeV electrons	38
Figure 21.	The dE/dx resolution vs. time	39
Figure 22.	Particle selectivity for π -K	40
Figure 23.	Particle selectivity for e-p	41
Figure 24.	Particle selectivity for π -p	41
Figure 25.	The spatial resolution for Bhabha electrons	43
Figure 26.	The spatial resolution for hadron tracks	43
Figure 27.	Drift distances from different points of the track	45
Figure 28.	The momenta vs. M^2 for hadron tracks	47
Figure 29.	TOF(measured)-TOF(expected) for pions	48
Figure 30.	dE/dx vs. apparent momentum	54
Figure 31.	Partial overlap	56
Figure 32.	A typical event of "type 1"	59
Figure 33.	The dE/dx display of "type 1" event	60
Figure 34.	The "type 3" event	62
Figure 35.	The acceptance vs. dE/dx	65
Figure 36.	R(q) upper limits at the 90 % confidence level	68
Figure 37.	Six antideuteron candidates	70
Figure 38.	One of the events with an antideuteron candidate track	72
Figure 39.	Cluster size vs. shower counter energy	73
Figure 40.	The projection of the last figure on the E axis	74
Figure 41.	One of the events with an antideuteron candidate track (a)	75

Figure 42. One of the events with an antideuteron candidate track (b)	76
Figure 43. One of the events with an antideuteron candidate track (c)	77
Figure 44. Lorentz invariant cross section for $\bar{d}$ production	79
Figure 45. The number of combinations vs. $\cos \alpha$	81
Figure 46. The invariant mass $M(\phi\pi)$	87

PREFACE

This thesis in high energy physics is based on the following papers:

A-I. R.L.Childers,Y.Oku,

ARGUS MAGNETIC FIELD MEASUREMENTS,

DESY-F15/83-01.

A-II. ARGUS Collab., H.Albrecht et al,

SEARCH FOR FRACTIONALLY CHARGED PARTICLES PRODUCED IN e^+e^- ANNIHILATION,

Phys. Lett. 156B (1985) 134.

A-III. ARGUS Collab., H.Albrecht et al,

OBSERVATION OF ANTIDEUTERON PRODUCTION IN ELECTRON-POSITRON ANNIHILATION AT 10 GeV CENTER-OF-MASS ENERGY

Phys. Lett. 157B (1985) 326.

A-IV. ARGUS Collab., H.Albrecht et al,

PRODUCTION AND DECAY OF CHARGED D^* MESON IN e^+e^- ANNIHILATION AT 10 GeV CENTRE-OF-MASS ENERGY

Phys. Lett. 150B (1985) 235.

A-V. ARGUS Collab., H.Albrecht et al,

PRODUCTION AND DECAY OF THE F MESON IN e^+e^- ANNIHILATION AT 10 GeV CENTRE-OF-MASS ENERGY

Phys. Lett. 153B (1985) 343.

A-VI. ARGUS Collab., H.Albrecht et al,

EVIDENCE FOR F^* MESON PRODUCTION IN e^+e^- ANNIHILATION AT 10 GeV CENTRE-OF-MASS ENERGY

Phys. Lett. 146B (1984) 111.

My main contributions to the ARGUS experiment were the magnetic field measurements, its parametrization (A-I) and the development of the drift chamber particle identification system (dE/dx-measurements). In this thesis after a short introduction, the ARGUS experiment is described. I put special weight on the description of the dE/dx measurement, not only because it was my main work in the ARGUS group, but also because the physics results which are included to this thesis rely very much on it. I have applied the excellent performance of the particle identification of the ARGUS experiment to particle searches, the results of which were published in the Physics Letters (A-II and A-III). These searches are described in detail in chapters 3 and 4 .

The dE/dx information has also played a very important role in the other work of the ARGUS collaboration (A-IV, A-V and A-VI). I have included these results in this thesis as examples which show the importance of the dE/dx particle identification in the ARGUS experiment. However I would like to mention here that in these studies, A-IV, A-V and A-VI, my contribution was limited to an indirect one, namely only through the supply of dE/dx and magnetic field information, as I was not directly involved in the analyses.

1.0 INTRODUCTION

Search for Fractional Charge and Heavy Stable Particles

In 1964 Gell-Mann and Zweig introduced the quark concept to systemize the huge number of 'elementary' particles found during the 1950's and 1960's at recently developed accelerators. Quarks were thought of as an underlying structure for the experimentally observed particles. With three different kinds of quarks (u,d and s) it was possible to build up all particles known at that time and also predict the then undiscovered Ω^- meson. The discovery of Ω^- was a big success for the quark model. Further support for the model was the result from a SLAC experiment (Stanford Linear Accelerator Center, California, U.S.A.) in 1969. This experiment was equivalent to the Rutherford scattering experiment in 1911 which revealed the existence of the nucleus inside the atom. In the SLAC experiment electrons with energy between 4.5 and 18 GeV were scattered against a proton target and the resulting angular distribution made the inner structure evident. A consequence of this discovery was an intense search for free quarks.

How can one search for the free quarks?

Since a proton contains three valence quarks, one would naively guess that free quarks are emitted when a proton is struck by another particle of high enough energy. It should also be possible to create a quark pair in an annihilation process in the same way as for example a lepton pair is produced.

$$\begin{array}{c} e^+ + e^- \rightarrow e^+ + e^- \\ \mu^+ + \mu^- \\ q + \bar{q} \end{array}$$

where $\bar{q}$ means an antiquark.

One of the most prominent features of quarks is that they have fractional charges in contrast to all other known particles which have integer charges, a feature which could be used to observe free quarks. Since the energy loss of a charged particle passing through material is proportional to the square of its charge, the energy loss of quarks with charges $1/3$ and $2/3$ will be only $1/9$ and $4/9$ respectively compared to that of a particle with charge one. The energy loss can be measured using e.g. a proportional chamber of the drift chamber type or a scintillating counter. In a proportional chamber the particle ionizes the gas in the chamber and the average ionization along the trajectory is measured. In a scintillator the

particle causes the material to scintillate i.e. to emit light and the amount of light is proportional to the energy loss of the particle.

The first searches for fractionally charged particles in high energy physics were performed by hadron collision experiments with solely negative results. Upper limits for the production cross section were given and the present limits are:

$$\begin{aligned}\sigma &< 4 \cdot 10^{-38} \text{ m}^2 \text{ for } Q = 1/3 \\ \sigma &< 6 \cdot 10^{-38} \text{ m}^2 \text{ for } Q = 2/3\end{aligned}$$

for a quark mass of less than 22 GeV/c². This means that free quark production is more than eight orders of magnitude smaller than normal hadron production.

In 1978 J. Orear proposed (ref.27) an explanation for the negative results of the quark searches in hadon collision experiments. This was based on the assumption that quarks undergo superstrong interaction, so that whenever a quark is produced in the presence of another quark not participating in the production mechanism (spectator quarks), the probability that the produced quark will interact with a spectator quark could be very high. This would make the probability of observing free quarks from hadron collisions much smaller than from e⁺e⁻-annihilation, where no spectator quarks are present.

At that time, no quark searches had been made in e⁺e⁻ annihilation, but recently several experiments have (ref.18-25) been made, again without observing any free quarks. The present upper limits for the free quark production, expressed as the ratio to the muon pair production cross section are shown in Figure 36 on page 68.

All of these negative experimental results do not mean that the quark model necessarily is wrong if the quarks are bound by a force which make them permanently confined in hadrons. However there is no rigorous proof for this and whenever improved tools become available, a search for free quarks should be performed.

The ARGUS experiment is especially well suited for a free quark search for the following reasons.

- If the assumption of J.Orear is correct, one would expect a more abundant production of free quarks in e⁺e⁻-annihilation than from hadron interactions.

- The amount of material between the interaction point and the first detector element corresponds to only 1.2 % of a nuclear interaction length (mean free path between inelastic interactions). This is less material than most other detectors of this kind and reduces the probability of quark absorption before detection.
- The fraction of tracks which can be identified from ionization (dE/dx) loss measurements is high and the dE/dx resolution is excellent.

A straight forward comparison of dE/dx properties of different experiments is not easy due to different track densities, essentially the consequence of different centre-of-mass energies and different background conditions. Nevertheless a comparison is given below (ref.26).

Detector	TPC	JADE	CLEO	ARGUS
Resolution (FWHM)	7.1	13	13.6	9.6
Efficiency	0.45	0.5	0.15	0.7

In this thesis, I report on a free quark search based on dE/dx measurements using the ARGUS drift chamber. The search was made for particles with ionization energy loss which is not expected for 'normal particles' (electrons, muons, pions, kaons and protons). The most probable energy loss of a charged particle traversing a gas is a function of the particle velocity and given by the following formula,

$$dE/dx = Q^2 \cdot f(\beta)$$

where Q is the charge of the particle and β is the velocity of the particle in units of light velocity, c. $f(\beta)$ varies as $1/\beta^2$ for $\beta \ll 1$ and as $\ln\beta$ for $\beta \approx 1$. β is given by the expression:

$$\beta = p / \sqrt{ (p^2 + M^2) }$$

where p is the momentum of the particle and M its mass.

For a fixed momentum, particles with different masses have different velocities and thus different energy losses. Therefore this search was sensitive to other stable particles with charge or mass different from the 'normal particles', i.e. free di-quarks with charge $4/3$ or charged stable gluinos, deuterons, tritons e.t.c..

Antideuterons are not 'exotic' in the usual sense, however their production in electron positron annihilation has never been observed before. The observation of antideuteron production is very important. Because the baryon production mechanism is not well understood yet, the observation provides information on the production of correlated antibaryon pairs of small relative momenta, which in turn will give more detailed information of the earlier stages of the fragmentation process.

The c and b quark

In 1974 the J/ψ resonance was discovered at the same time at BNL (Brookhaven National Laboratory New York U.S.A.) (ref.44) and at SLAC (ref.45) as a narrow resonance with a mass of $\sim 3.1 \text{ GeV}/c^2$. The most exciting property of the J/ψ was its small partial width for direct decays into hadrons, which turned out to be suppressed by roughly a factor of 10^4 compared to the expectation for a conventional meson of 3 to 4 GeV/c^2 mass. An intuitively simple and now accepted explanation for this experimental fact was offered by the quark model, with the introduction of a fourth quark, c (charm), which carries a new quantum number such that the decay $c \rightarrow q$ where $q = u, d$ or s can proceed only via the weak interaction. According to this explanation the J/ψ was assumed to be a $c\bar{c}$ bound state. The spectrum of $c\bar{c}$ states in terms of spin and parity, J^P , follows directly from the spin $1/2$ nature of the quark and is analogous to that of positronium. The observation of these predicted states confirmed this picture of the quark model. The existence of a fourth quark implies that the SU(3) nonet of $8 + 1$ mesons will be replaced by a hexadecimet of $15 + 1$ states, as shown in Figure 1 on page 5. Apart from the ordinary SU(3) resonances with $c = 0$, the hexadecimet contains six states with open charm, $c = \pm 1$ and one $c\bar{c}$ state with hidden charm. The quark contents as well as the names given to these charmed mesons are shown in the figure.

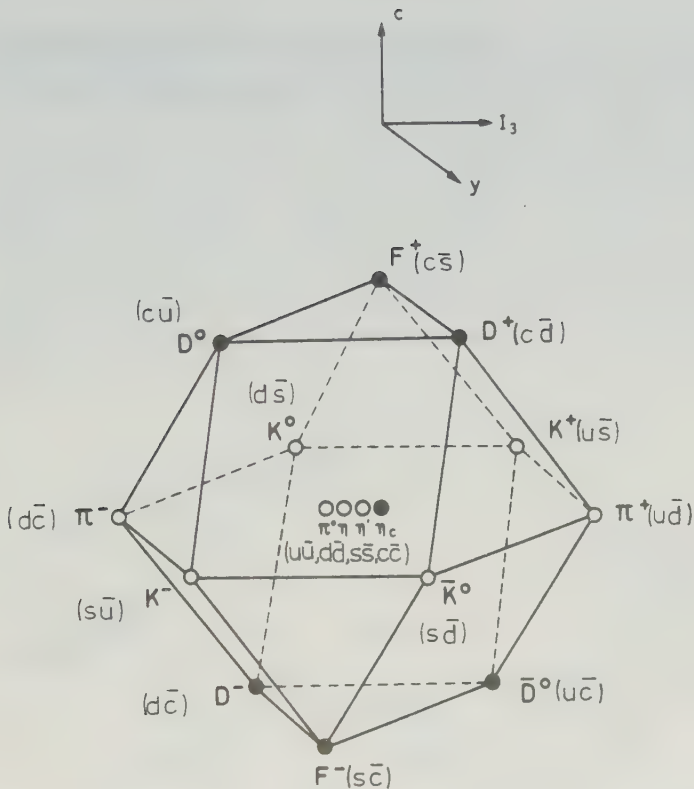


Figure 1. The hexadecimet of the pseudoscalar mesons

Short descriptions of studies of the F meson, as well as the F^* and D^* meson, which are the excited states of the F and D meson respectively, are given in the chapter 5, as examples which show the importance of dE/dx particle identification in the ARGUS experiments. However charm physics is not a theme of this thesis.

In 1977 the Υ resonance was discovered at FNAL (Fermi National Accelerator Laboratory, Illinois U.S.A.) (ref.46) as a narrow resonance with a mass of $\sim 9.5 \text{ GeV}/c^2$ in the $\mu^+\mu^-$ invariant mass spectrum produced via,

$$400 \text{ GeV } p + \text{Be} \rightarrow \mu^+\mu^- + X$$

where X includes any other reaction products. By an argument similar to that of the J/ψ , the Υ was associated with a new heavy quark b and the Υ was interpreted as a $b\bar{b}$ bound state. Υ spectroscopy is also one of the main themes of the ARGUS experiment.

2.0 GENERAL DESCRIPTION OF THE EXPERIMENT

2.1 DORIS II STORAGE RING

A schematic picture of the acceleration chain feeding the electron-positron storage ring DORIS II (Doppel Ring Speicher) with particles is shown in Figure 2. Positrons are produced in the linear accelerator LINAC II by bombarding a tungsten filament with electrons. After being accelerated to 450 MeV, the positrons are accumulated in the small storage ring PIA (Positron Intensity Accumulator). Both positrons and electrons (from LINAC I) are fed into the synchrotron DESY (Deutsches Elektronen SYncrotron), where they are accelerated to the energy required for injection into DORIS II.

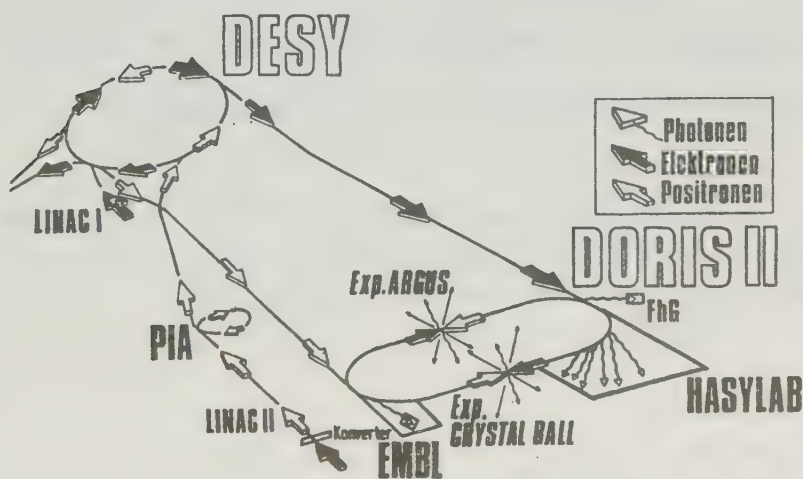


Figure 2. The electron-positron storage ring DORIS II:

A schematic picture of the acceleration chain feeding the electron-positron storage ring DORIS II with particles

DORIS consisted originally of two vertically separated beam tubes which crossed each other at two points. This structure gave rise to the name of the storage ring. DORIS came into operation in 1974 and was originally built for a maximum energy of 3.5 GeV per beam. In this energy range the

highest luminosity (see 2.2) was achieved by operating the storage ring in a multibunch mode i.e. filling each beam tube with a large number of bunches. The two tube structure also permitted storage of particle combinations other than e^+e^- such as e^-e^- , e^+e^+ .

After the discovery of the T -meson in 1977 at FNAL, DORIS was upgraded to a beam energy of 5 GeV (DORIS II) to achieve a center of mass energy of 10 GeV, sufficient to produce this particle and its excited states. As a consequence of this rise in energy, the operation of the storage ring was changed from multibunch to single bunch operation which at this energy gave the highest luminosity.

In 1982 DORIS II was upgraded once more in order to reach above the limit for production of B (Beauty) mesons¹,

2.2 LUMINOSITY

The event rate N corresponding to a cross section σ is given by

$$N = L \cdot \sigma,$$

where L is the luminosity. Thus the higher the luminosity, the higher the event rate for the reaction.

Consider head on collision between bunches of particles

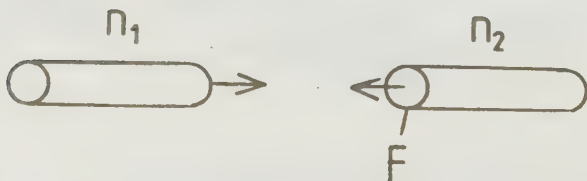


Figure 3. Collision between bunches of particles

¹ Bound states of one b ($\bar{b}$) quark and one antiquark (quark) such as $\bar{u}, \bar{d}, \bar{s}, \bar{c}$ (u, d, s, c).

If we define n_1 and n_2 as the number of particles per beam, F as the beam cross section, B as the number of bunches per beam and f as the rotation frequency, then the luminosity is given by (ref.29):

$$L = (n_1 \cdot n_2 \cdot f \cdot B) / F.$$

A gaussian particle density distribution with rms radii $\sigma(x)$, $\sigma(y)$ has a cross section of

$$F = 4 \pi \cdot \sigma(x) \cdot \sigma(y)$$

Expressing L in terms of the beam currents, $i = n \cdot e \cdot f \cdot B$ (e is the electron charge), one has

$$L = i_1 \cdot i_2 / (4 \pi \cdot e^2 \cdot \sigma(x) \cdot \sigma(y) \cdot f \cdot B)$$

For a typical set of e^+e^- storage ring parameters:

$$\begin{aligned} B &= 1 \\ f &= 10^6 \text{ sec}^{-1} \\ i &= 50 \text{ mA} \approx 3.3 \cdot 10^{17} \text{ e sec}^{-1} \\ \sigma(x) &= 0.1 \text{ cm} \\ \sigma(y) &= 0.01 \text{ cm} \end{aligned}$$

the luminosity L is $10^{31} \text{ cm}^{-2}\text{sec}^{-1}$, leading to $N = 10$ events per second for $\sigma = 1 \mu\text{b}$ ($1 \text{ b} = 10^{-24} \text{ cm}^2$).

The integrated luminosity L_1 in the time interval t_1 to t_2 is given by

$$L_1 = \int_{t_1}^{t_2} dL/dt \, dt$$

and the number of events N' in this time interval is given by

$$N' = L_1 \cdot \sigma.$$

Thus it is very important to know L_1 to obtain σ from the experimentally observed number of events.

For Bhabha scattering events, i.e. elastic electron-positron scattering, the cross section is well known. In lowest order perturbation theory the differential cross section for scattering at an angle ϑ with respect to the incoming particle direction is given by:

$$d\sigma/d\Omega = \alpha^2/2s \cdot ((q'^4+s^2)/q^4 + 2q'/q^2s + (q'^4+q^4)/s^2)$$

with $q^2 = -s \cdot \cos^2\vartheta/2$
 $q'^2 = s \cdot \sin^2\vartheta/2$
 $\alpha = 1/137$
 s : the center of mass energy squared

The angular distribution possesses a sharp peak in the forward direction which is seen from Figure 4.

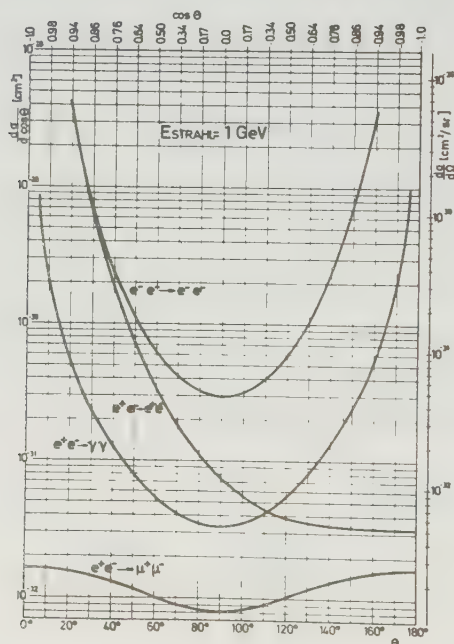


Figure 4. The differential cross section:

The differential cross section for the processes $e^+e^- \rightarrow e^+e^-$, $e^-e^- \rightarrow e^-e^-$, $e^-e^- \rightarrow \gamma\gamma$ and $e^-e^- \rightarrow \mu^+\mu^-$ for a beam energy of 1 GeV (ref. 29).

Exploiting this fact, in the ARGUS experiment the luminosity is measured using the end cap shower and time-of-flight counters (see 2.3.4 and 2.3.5).

2.3 THE ARGUS DETECTOR

The ARGUS (A Russian German United states Swedish) collaboration and the ARGUS detector are shown below.

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⁵ McGill University, Montreal, Canada.

⁶ Supported by the Natural Sciences and Engineering Research Council, Canada.

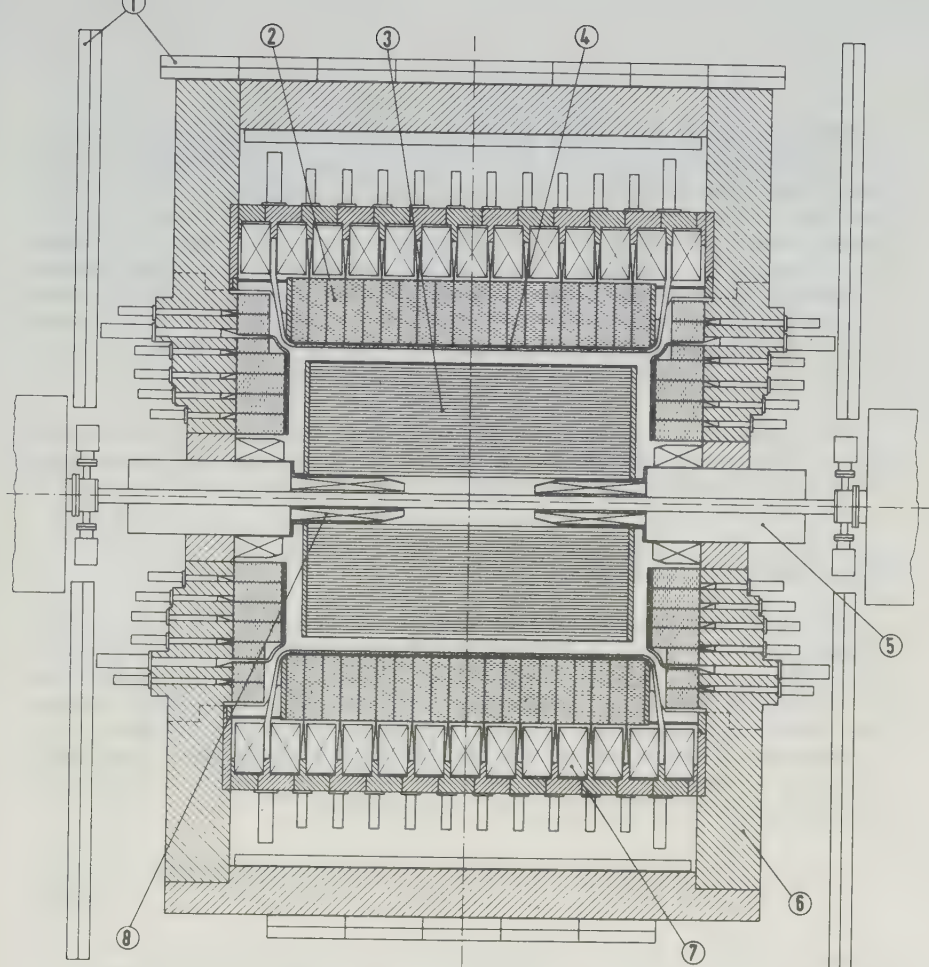
⁷ Supported by the US National Science Foundation and a University of Kansas Faculty Improvement award.

⁸ Present address: CERN, Geneva, Switzerland.

⁹ Supported by the Swedish Research Council.

¹⁰ On leave of absence from the University of Stockholm, Sweden.

¹¹ Supported by the US Department of Energy, under contract DE-AS09-80ER10690.



- | | |
|------------------------|-------------------------|
| 1. Myon Kammern | Muon chambers |
| 2. Schauerzähler | Shower counters |
| 3. Driftkammer | Drift chamber |
| 4. Flugzeitzähler | Time of flight counters |
| 5. Mini Beta Quadrupol | Mini beta quadrupole |
| 6. Eisenjoch | Iron yoke |
| 7. Hauptspule | Solenoid coils |
| 8. Kompensationsspulen | Compensation coils |

Figure 5. The ARGUS detector as of 1984

ARGUS is one of two detectors installed at the DORIS II storage ring. It is a magnetic detector of the general purpose type employing a high magnetic field, good charged particle tracking and momentum measurement and fair energy resolution for electromagnetically showering particles. Tracks of charged particles are made 'visible' in a cylindrical drift chamber. A solenoidal magnetic field bends the charged particles in helical trajectories which allows a determination of their momenta. A set of shower counters measure the energy of electrons and photons. The iron return yoke of the magnet is used as a hadron filter to select muons, the only charged particle able to traverse such a thickness of material.

After defining the ARGUS coordinate system, each detector component will be described. The emphasis is put on these detector components which play a major role in this work.

2.3.1 The coordinate system

The coordinate system used for the ARGUS detector is a right-handed cartesian system (x,y,z) with the x-axis horizontal, the y-axis vertical and the z-axis pointing along the nominal drift chamber axis in the direction of the positron beam (see Figure 6 on page 15). The origin of the coordinate system coincides with the nominal centre of the drift chamber. In a cylindrical coordinate system the notation is (ρ,z,φ) with $\rho = \sqrt{(x^2 + y^2)}$ and $\varphi = \arctan(y/x)$. For polar coordinates (R,ϑ,ϕ) ϑ is defined as $\arccos(z/\rho)$ and R as $\sqrt{(x^2 + y^2 + z^2)}$ respectively.

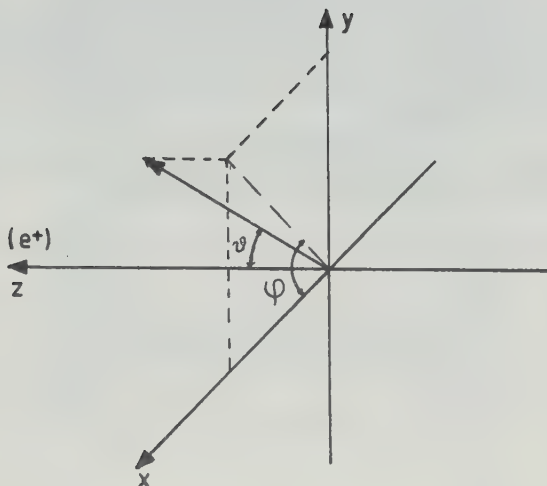


Figure 6. The ARGUS coordinate system

2.3.2 The mini- β quadrupoles, the compensation coils and the ARGUS magnet.

As was shown in section 2.2 the luminosity is inversely proportional to the transverse dimension of the beams. Thus, it is essential to focus the beams as much as possible to get the highest possible luminosity. To achieve this two mini- β quadrupoles were installed, one at each end of the detector. Due to the short distance between the magnets of the storage ring and the detector these quadrupoles had to be integrated into the detector in a way which is shown in Figure 5 on page 13. Thereby the quadrupoles are quite close to the interaction point which is favourable from a focusing point of view. On the other hand this solution leaves a dead area in the forward regions up to a polar angle of about 300 mrad, which can not be equipped with detector elements (time-of-flight counters and shower counters). Another disadvantage is that the main magnetic field of the ARGUS detector is somewhat distorted by the field of the mini- β quadrupoles.

To protect the field of the mini- β quadrupoles from the main solenoidal field they are surrounded by small compensation coils (the outer compensation coils).

There are also two inner compensation coils surrounding the vacuum pipe and extending as close as 0.45 m to the interaction point. The purpose of these coils is to protect the beam from being influenced by the radial components of the solenoid field.

The ARGUS magnet is of the solenoid type. A field of approximately 0.8 Tesla is provided by 13 separate coils of 3 m diameter.

Magnetic field measurements and the parametrization. (see ref. A - I)

The magnetic field intensity in the interior of the ARGUS detector was measured in April 1982, before the installation of the detector elements. The volume in which most of the measurements were made was essentially that to be occupied by the drift chamber (Figure 5 on page 13), since in that region the field has to be known as precisely as possible to achieve a good momentum determination. In the other regions, which are occupied by the shower counters and the time-of-flight counters, the field values are theoretically calculated by a program giving a typical error of a few per cent, which is sufficient. The BEBC-field mapping system from CERN (European Laboratory for Particle Physics, Geneva, Switzerland) was used to make and record the measurements. A sketch of the mechanical framework for holding and moving the hall probes is shown in Figure 7 on page 17

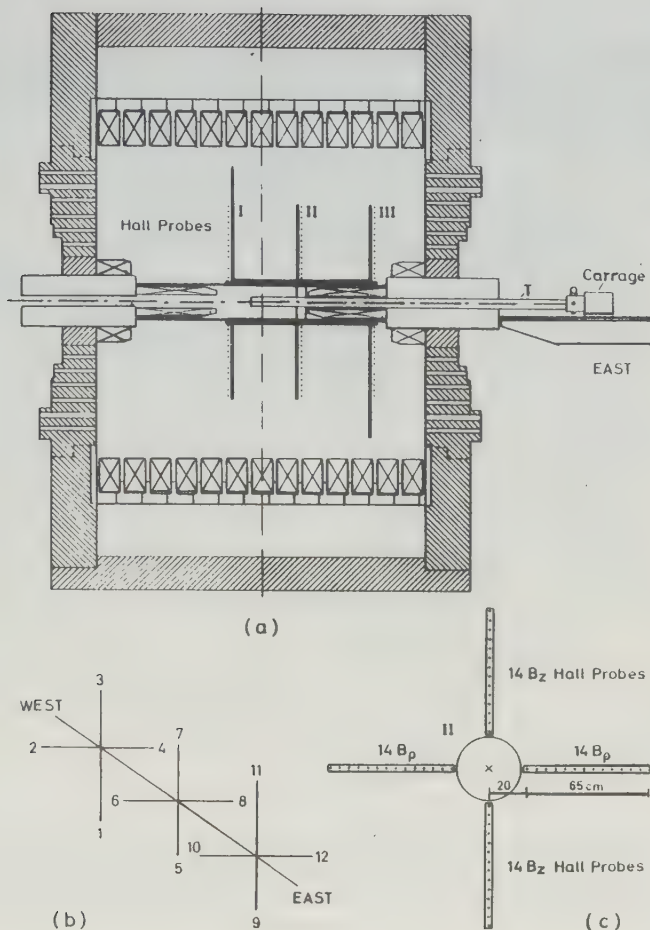


Figure 7. The Mechanical mounting of probes: a) The overall view b) The schematic drawing of probe support arms c) The end view of one support.

The supports I, II and III on which the hall probes were mounted, were fixed with respect to one another and could be moved along the z axis as a unit by means of the hollow tube T. Measurements were made for the axial (B_z), the radial (B_ρ) and to a lesser extent the tangential (B_θ)

components, for three different field intensities of the inner compensation coils, which correspond to 0 %, 50 % and 100 % compensation. The spacing between the measuring points was 50 mm in z as well as in the radial (ρ) direction and 30° in φ^2 (Figure 8)

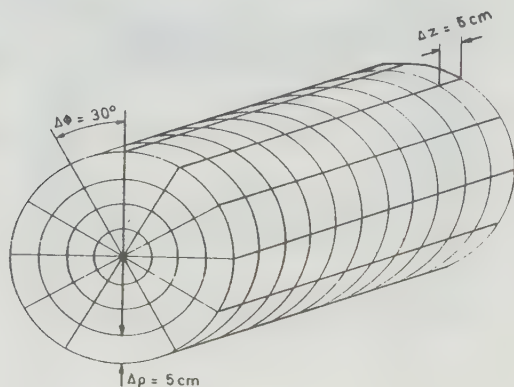


Figure 8. The measuring grid

The probes were calibrated at CERN against an nuclear magnetic resonance (NMR) probe. Figure 9 on page 19 displays the measured B_z for 0 % inner compensation. The drop in the field values at small ρ and large z is due to the influence of the outer compensation coils.

² The coodinate system is defined in (2.2.1)

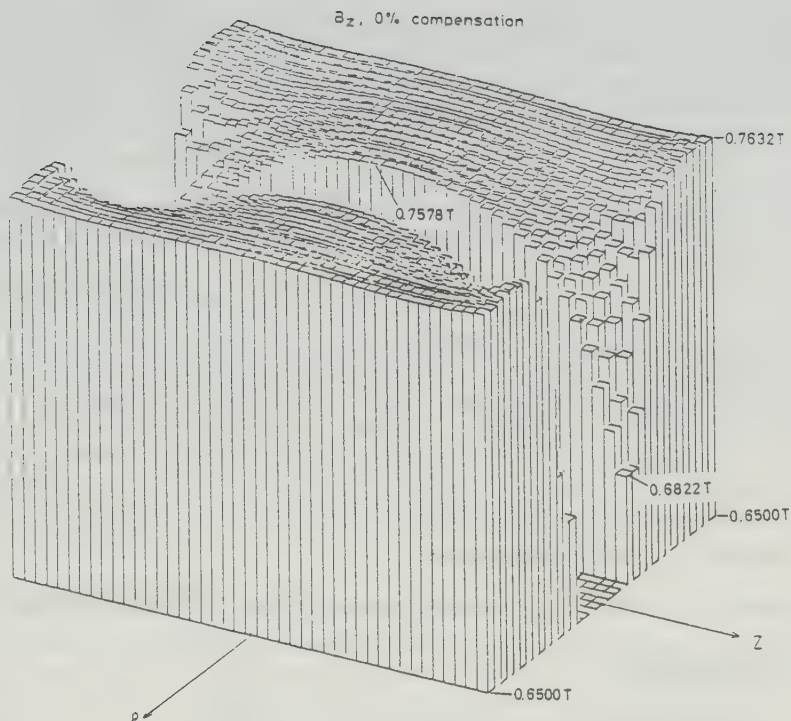


Figure 9. The measured field value

a. The magnetization

The readings of one probe as a function of the magnet current are shown in Figure 10 on page 20

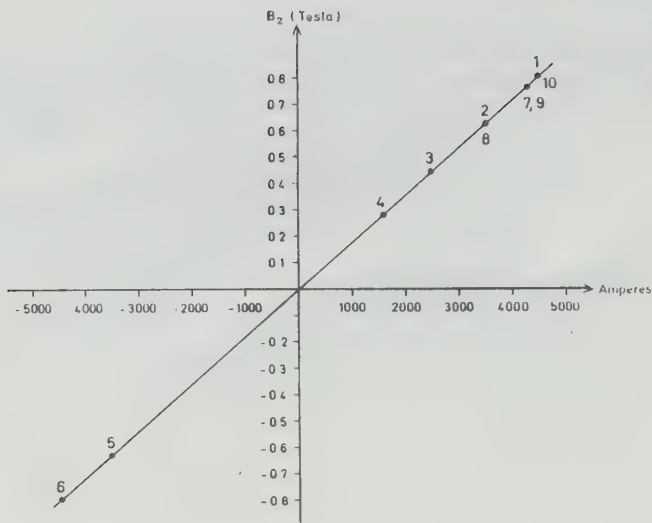


Figure 10. The magnetization

The data are well fit by a straight line with a rms deviation of 7 Gauss.

b. The symmetry

Two types of geometrical symmetry were checked.

1. The symmetry in φ

For fixed z and ρ the quantity D , which is defined as:

$$D = (B_z - \langle B_z \rangle) / \langle B_z \rangle$$

was determined as a function of φ to give the field asymmetry in φ . In the above expression B_z means the measured field value at a point (ρ, z, φ) and $\langle B_z \rangle$ is the average of B_z over all φ -values for fixed z and ρ . The standard deviation of the resultant D -distribution was less than 0.1 % for all inner compensation fields used.

2. The symmetry about the midplane ($z = 0$)

The distribution of the quantity D_z , where

$$D_z = (B_z(+z) - B_z(-z)) / < B_z >$$

was determined in a similar way as a function of z for fixed ρ and φ to obtain the asymmetry with respect to the $z=0$ plane. $B_z(+z)$ and $B_z(-z)$ are the measured field values at the points (ρ, z, φ) and $(\rho, -z, \varphi)$ respectively and $< B_z >$ is the average of the two. The standard deviation of the D_z -distribution was also less than 0.1 % for all inner compensation configurations.

Therefore the conclusion is that the field is symmetric both in φ and with respect to the $z = 0$ plane within the measurement error which is ~ 0.1 %.

c. The tangential component

Although a φ component is not expected for a perfect solenoid field, we have nevertheless observed values of B_φ ranging from -100 Gauss to +200 Gauss. The observed values of B_φ can be satisfactorily explained by the following effects: (1) a contribution due to longitudinal components of the current between the coils and (2) an effect due to tilted probes (i.e. a measurement error). (1) was large enough to be measured in the region close to the coil but turned out to be negligible in the volume intended for the drift chamber.

d. The parametrization

The measured field values were corrected for an estimated misalignment of the probes and for the fact that the field should be described by Maxwell's equations according to a procedure which is described in ref. A-I. These corrected values were parametrized for each of the 36 drift chamber layers using simple polynomials. The number of parameters was less than 7 for each layer and the error in the field values calculated using the parameterization is less than a few parts per thousand. This method has the following advantages:

1. The program which supplies the field value is very fast compared to a parametrization using Bessel functions or Legendre polynomials which are the solutions to Laplace's equation. The importance of minimizing the computing time becomes clear when one considers the amount of data which has to be processed (see (3.1.1)).
2. The accuracy is better than that which can be achieved with a look-up table.

2.3.3 The drift chamber

a. THE DESIGN

The drift chamber is a cylinder of 2 meter length and 172 cm diameter. Along the cylinder axis is a hole of 30 cm diameter for the beam pipe. The inner drift chamber wall is made of 3.3 mm thick epoxy carbon fiber and the outer wall is 6 mm aluminum. The end plates are 30 mm thick aluminum plates to take up the forces of the approximately 30.000 wires strung between them. There are 5940 identical drift cells contained in one gas volume to minimize multiple scattering effects from vessel walls and to meet the requirements of as large a solid angle acceptance as possible, high granularity and homogeneity. A drift cell is defined by a number of potential wires strung between the end plates of the drift chamber. The pattern of these potential wires as seen from the end plate defines an almost square drift cell as can be seen from Figure 11.

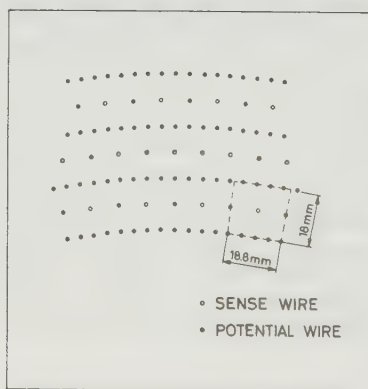


Figure 11. The pattern of the potential wires as seen from the end plate

In the center of each cell a signal wire is situated. The electric drift field generated by the potential wires gives concentric equipotential lines for most of the cell which results in a very simple relation between the

drift time and the distance to the signal wire. Only in the corners are the field lines distorted, but this is not too severe since a particle traversing a corner of one cell normally also traverses the central region of the neighbouring cell in the same layer. (Figure 12 on page 24).

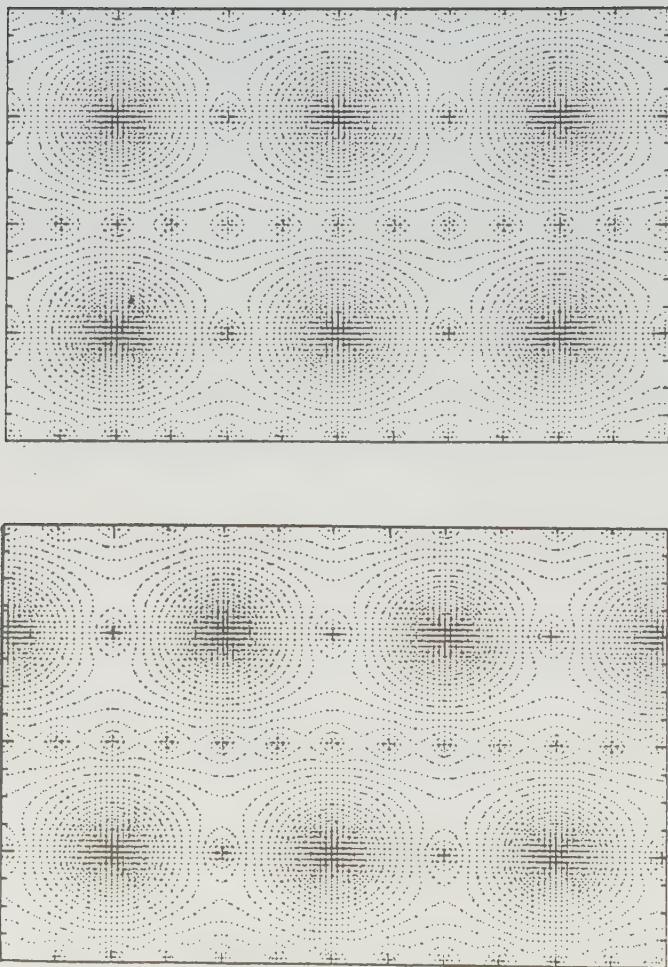


Figure 12. Equipotentials of the drift chamber:

Two extreme cases of wire positions in adjacent layers are shown

The drift cells are organized in 36 layers, 18 of which provide stereo views for axial coordinate measurements. (Figure 5 on page 13). Com-

pared to the charge division method, this method demands less electronics and does not require high gas amplification, which would disturb the dE/dx measurements because of saturation effects. Each $30\text{ }\mu\text{m}$ thick tungsten sense wire is positioned by feeding it through gold plated pins which are crimped around the wire. The pins are contained in a plastic holders sitting in precisely drilled holes in the end plates. The $76\text{ }\mu\text{m}$ thick copper-beryllium potential wires are fed through copper pins directly connected to the drift chamber end plates and fixed by the crimping method. These wires are thus kept at ground potential. The small diameter of the potential wires minimizes the amount of material in the chamber and thus the effect of multiple scattering. The material in the active region of the chamber along its radius corresponds to as little as 0.55 % of a radiation length.

The stereo angle increases from 40 mrad for the inner most stereo layer to 80 mrad for the outer most stereo layer. The values are chosen to limit to 1 mm the maximum radial displacement of a sense wire from the center of a cell, as defined by the potential wires. This displacement is an effect of the different angles of the sense wires as compared to the potential wires and is thus z dependent. (Figure 13).

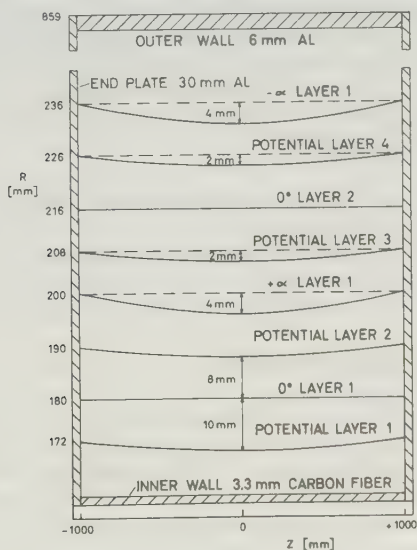


Figure 13. Drift chamber cross section parallel to the beam

A displacement of 1 mm leads to a change in gas amplification of 10 %. To fulfill the requirement of limited displacement and still allow stereo angles as large as possible, the potential wires also had to be tilted according to a certain pattern.

The high voltage distribution among the sense wires is highly segmented and there are 157 groups with separate HV cables. This makes it possible to operate a major part of the drift chamber even if part of it, for example is disturbed by too high background rates. The high voltage system has a stability of ± 0.5 V and is equipped with overcurrent protection.

b. GAS

The chamber is operated with a 97 % propane (C_3H_8), 3 % methylal ($CH_2(OCH_3)_2$) gas mixture. The advantages of using propane are its long radiation length, which minimizes the multiple scattering, and its small diffusion which provides a well defined drift time with good momentum resolution as a consequence. Propane also has a narrow Landau distribution and hence much better dE/dx resolution than the frequently used argon gas. In the low momentum region the particle separation improves proportional to the resolution but since the relativistic rise in propane is smaller than that in argon, only a small improvement can be obtained for fast particle separation. A small amount of methylal is added to decrease the tendency of propane to polymerize. The polymerisation will create a thin layer of heavy hydrocarbons on the potential wires which might ruin the operation of the chamber (ref.4).

The chamber is operated at a constant pressure slightly above one atmosphere to minimize multiple scattering. The gas is circulated in a closed system with a gas flow as high as 12 m³/h to ensure a homogeneous gas distribution in the chamber and to avoid temperature gradients. Because the system is closed, the fresh gas consumption is only 50 l/h.

c. MEASUREMENTS WITH THE DRIFT CHAMBER

A charged particle passing through the drift chamber ionizes a number of gas molecules. Under the influence of the electric field, the primary electrons and ions start to drift along the field lines of the cells. The electrons drift towards the signal wire and the ions towards the nearest potential wire. The electrons drift approximately 1000 times faster than the ions. In the immediate vicinity of the sense wire the electrons gain enough energy from the increasing field density to be able to further ionize gas molecules and an electric avalanche is built. The number of

electrons increases on average by a factor of 10^4 . This large number of electrons together with the slowly moving cloud of ions created close to the sense wire give a measurable signal on the sense wire.

Connected to each sense wire is a preamplifier, directly mounted on one of the drift chamber plates, with an amplification factor of 20. The signal is then fed into a main amplifier which again amplifies the signal about a factor of 20. When the signal exceeds the threshold of a discriminator, it starts a scalar which counts at the clock frequency of the TDC (Time-to-Digital-Converter). The TDCs of the ARGUS drift chamber are operated in a 'common-stop-mode', which means that all TDCs are stopped at a preselected time after the e^+e^- collision. The TDC measured value, which is stored in a 9-bit-word, is linearly related to the drift time of the electrons from the particle trajectory to the sense wire. The smaller the TDC value is, the larger the drift time. The clock frequency of the TDCs is 10^9 Hz which means that two consecutive readings correspond to a time difference of 1 ns. The slope and the zero point crossing are regularly checked for all TDC channels with the help of a test pulse chain and the TDCs are calibrated to remove unit dependent effects, temperature and voltage fluctuations as well as the time differences due to different external cable lengths.

The relation between the measured TDC value and the closest distance of the track to the sense wire is shown in Figure 14 on page 28.

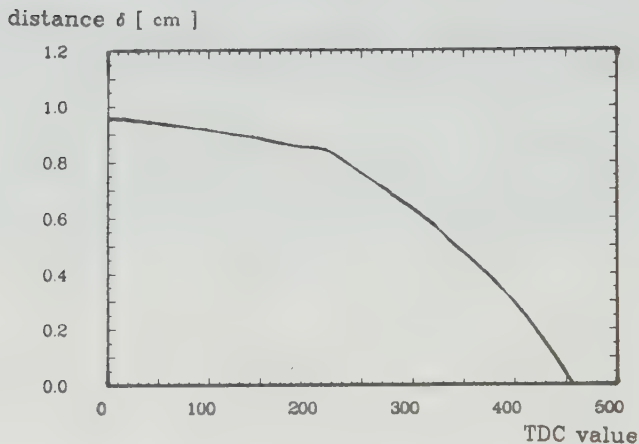


Figure 14. The space-time relation:

The distance from the wire vs. TDC value is shown (ref.4).

The first step of the pattern recognition procedure is to find fired sense wires belonging to a common track. Although the distance of the track from the sense wire is known from the TDC measurement, it is not known whether the particle passed to the right or the left of the wire. One can, however, imagine a circle around each sense wire with a radius corresponding to this distance and the correct solution for the trajectory can be found from the knowledge that it has to touch all these circles. The R - φ projection of a typical multihadron event is shown in Figure 15 on page 29.

EXP 2
 RUN 4211
 EVI 1723
 TRI 030050
 PROJ R2
 SCAL 0.868

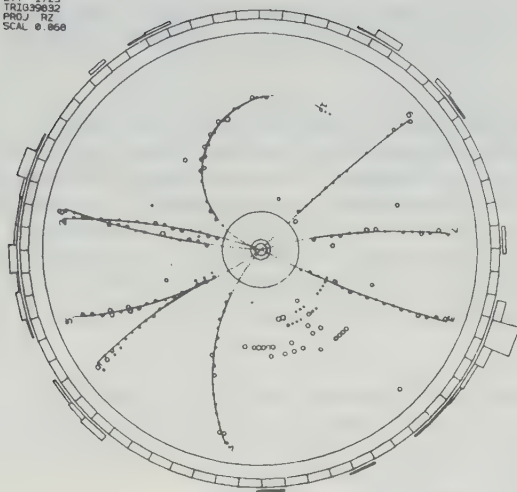


Figure 15. A typical multihadron event

A track is completely described by the following five parameters:

1. the bending radius
2. the closest distance, D , of the track to the origin
3. the azimuthal angle φ_0 in the track point (x_0, y_0) closest to the origin
4. the z -coordinate, z_0 , of the track point closest to the origin
5. the polar angle ϑ with respect to the z -axis

A fit of these parameters, which is performed as a final step in the track finding process, finds the best solution by minimizing the sum of the square of the difference between the measured and the fitted distances from the sense wires.

$$\chi^2_m = \sum_i (M(i) - F(i))^2 / \sigma^2(i) \quad (2.3-1)$$

with $i = 1, N$

where $M(i)$ and $F(i)$ are the measured and fitted distances, $\sigma(i)$ is the estimated space resolution and N is the number of measured points on the track.

The standard deviation of the residual distribution $R_i = M(i) - F(i)$, is a measure on the quality of the space-time relation. In the ideal case one would expect this distribution to be gaussian with a width dependent on the distance of the track from the sense wire. Provided the σ values are estimated correctly and the residuals are distributed according to a gaussian, the χ^2 -distribution for a sample of tracks with N measuring points corresponds to a χ^2 -distribution with $(N-5)$ degrees of freedom, since the track is fully determined by the above mentioned five parameters.

The probability density is described (ref. 41) through

$$f(\chi^2) = \frac{1}{2^{n/2} \Gamma(n/2)} \cdot (\chi^2)^{(n-2)/2} \cdot \exp \left\{ -\chi^2 / 2 \right\}$$

with a Gamma funktion

$$\Gamma(a) = \int_0^{\infty} e^{-t} \cdot t^{a-1} dt$$

n = the number of degrees of freedom

The deviation from the expected form can be expressed by the χ^2 -probability for the track (ref.41)

$$\text{prob}(\chi_m^2) = \int_{\chi_m^2}^{\infty} f(\chi^2) d\chi^2$$

The distribution of $\text{prob}(\chi_m^2)$ is sensitive to $\sigma(i)$, as can be seen from the formula (2.3-1). With correct $\sigma(i)$ values and gaussian distributed residuals, the $\text{prob}(\chi_m^2)$ distribution should be flat. In Figure 16 on page 31 a measured $\text{prob}(\chi_m^2)$ distribution is shown. One sees a sharp peak at small $\text{prob}(\chi_m^2)$, which is due to the multiple scattering of low momentum tracks against gas molecules or wires. Further contributions could come from errors in TDC units or wrong assignment of hits to the track.

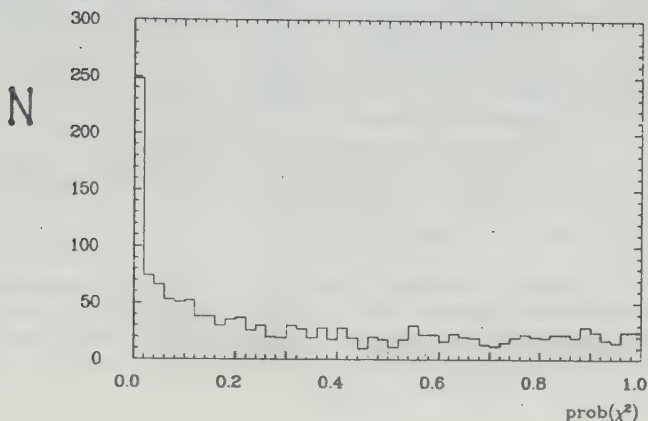


Figure 16. A measured χ^2 -probability distribution:

N is the number of tracks

For each signal wire an ADC (Analog-to-Digital-Converter) unit is also connected. The ADC unit measures and digitizes the energy deposited on the sense wire of the drift cell. With a number of ADC values along a track one can determine the energy loss distribution and the most probable energy loss of the particle. They depend on the charge and the velocity of the particle and with a knowledge of the particle momentum, identification is possible in certain momentum regions. This will be described in more detail in the next section.

d. THE dE/dx INFORMATION

In a classical formulation due to Landau, the energy loss distribution in a medium is given by

$$f(\lambda) = 1 / \sqrt{2\pi} \cdot \exp(-1/2(\lambda + \exp(-\lambda))),$$

The reduced energy variable λ represents the normalized deviation from the most probable energy loss $E(mp)$

$$\lambda = (E - E(mp)) / \xi$$

where E is the actual energy loss and ξ the average energy loss. ξ is given by the following expression:

$$\xi = K \cdot Z / A \cdot \rho / \beta^2 \cdot t$$

$$\text{where } K = (2\pi \cdot N \cdot Q^2 \cdot e^4) / mc^2,$$

N : Avogadro's number,

e, m : the electron charge and mass,

Z, A, ρ : the atomic number, mass and density of the medium,

Q : the charge of the particle,

t : the track length.

In Figure 17 on page 33 the energy loss distribution of a charged particle in a gas is compared to the distribution derived from a simple gaussian theory and from the Landau expression. Notice the long tail at very large energy losses, corresponding to events where one or more energetic electrons (δ -electrons) have been produced.

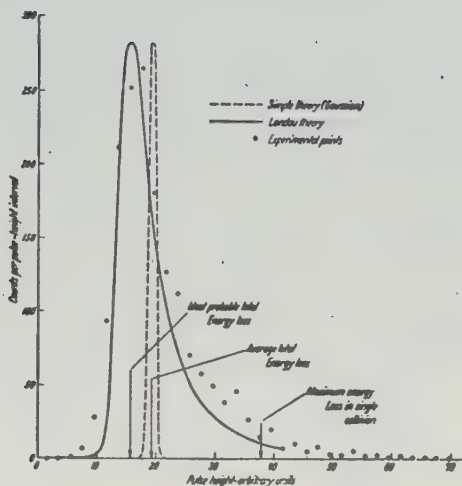


Figure 17. The energy loss distribution:

A comparison of the experimental energy loss distribution, in an argon carbon dioxide counter, with the distribution computed using a simple Gaussian theory and the Landau expression (ref. 8)

In the ARGUS experiment the truncated mean method is used to estimate the most probable energy loss of the particle. In this method, a fixed fraction of the measuring points with the largest dE/dx values (in the ARGUS case 30 %) is discarded and the average is taken for the remaining dE/dx sample. In the case of ARGUS, also a fixed fraction (10 %) of the samples with the lowest dE/dx value is discarded. This has the effect of reducing the influence of the bad sense wires making the distribution of the truncated average energy loss more gaussian.

In Figure 18 on page 34, this distribution as measured by the ARGUS drift chamber for approximately 10,000 particles, is shown as a function of the particle momentum. One can see that electrons, pions, muons, kaons, and protons are clearly separated in the lower momentum region. One can also see deuterons from beam gas or beam wall interactions.

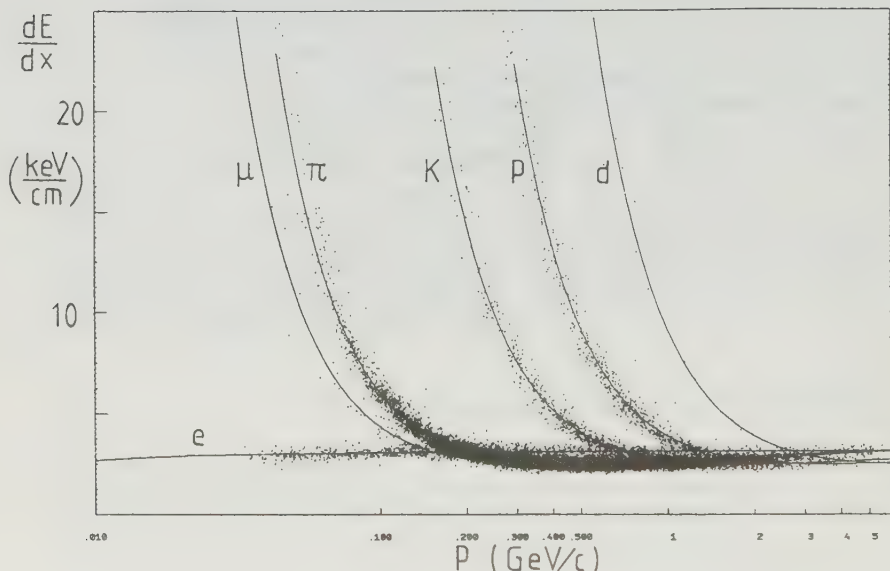


Figure 18. The truncated mean of the energy loss vs. momentum:

The truncated means measured by the ARGUS drift chamber for approximately 10,000 particles are shown as a function of their momentum. Electrons, pions, muons, kaons, and protons are clearly separated. One can also see deuterons from beam gas or beam wall interactions.

1. Corrections

To extract dE/dx from the raw ADC readings, corrections due to the dependence of the charge collection on the angle between the track and the sense wire are applied. Differences in the charge integration time for different drift distances and gas amplification dependence on

gas temperature and pressure also give rise to corrections, as well as the track length in the cell.

Figure 19 on page 36 shows the dependence of the collected charge (normalized to 1.8 cm track length) on the angle between the track and the sense wire for different gas amplifications (i.e. different voltages at the sense wire). When the track is parallel to the sense wire all the electrons from the track arrive at the sense wire at essentially the same time and make an electric avalanche. If on the other hand the angle between the track and the sense wire is around 90 degrees, the electrons from different points of the track hit the sense wire at different times because of the different drift lengths. The avalanche created by the electron with the shortest drift distance causes a local change of the electric field which influences the drift and collection of the electrons with larger drift distances.

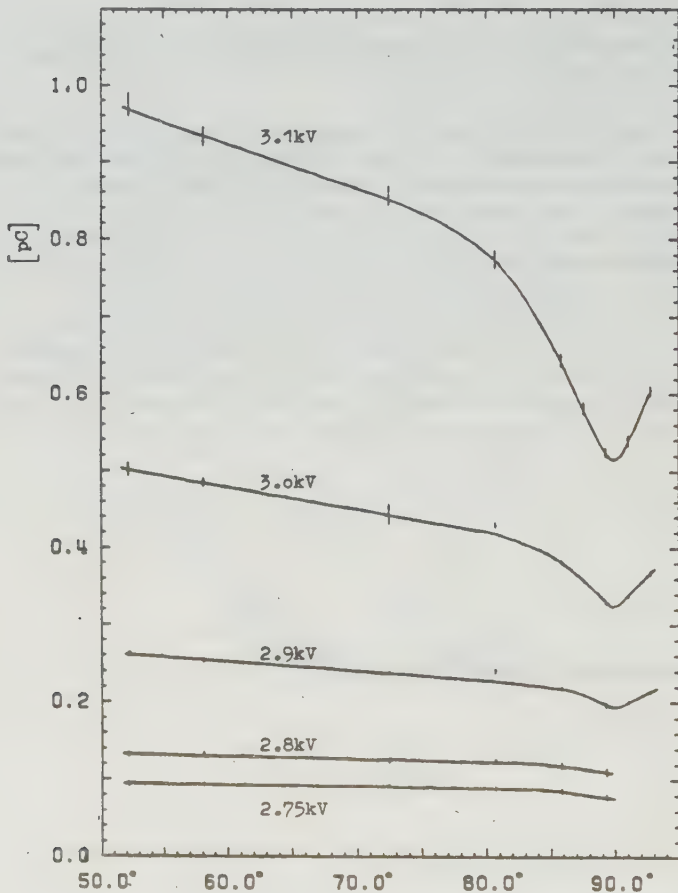


Figure 19. The dependence of the collected charge on the angle of the track:

The dependence of the collected charge (normalized to 1.8 cm track length) on the angle between the track and the sense wire for different gas amplifications (i.e. different voltages at the sense wire) is shown.

The calibration constants were obtained mainly using Bhabha scattered electrons. In particular the mean gas amplification is determined every 5 nb^{-1} of collected luminosity. The advantage of using

the Bhabha scattering process is its high rate which offers a precise calibration to be performed. In addition this process can easily be identified by its simple event shape and because the energy deposition of the electrons in the shower counters has to be equal to the beam energy (the ARGUS shower counter system will be described in 2.3.5). For polar angles in the range 40° to 140° , which were used for the calibration, the Bhabha scattering cross section is about 12 nb at a center of mass energy of 10 GeV, corresponding to an event rate of ~ 0.1 Hz. This should be compared to the muonic event rate ($e^+ e^- \rightarrow \mu^+ \mu^-$) of ~ 0.005 Hz and the hadronic event rate ($e^+ e^- \rightarrow \text{hadrons}$) of ~ 0.02 Hz.

2. The resolution

In Figure 20 on page 38 the distribution of energy loss for 5 GeV electrons is compared to a gaussian distribution. As can be seen the agreement is excellent over more than 3 orders of magnitude. For this data sample the resolution was 4.4 %. Among all data samples used in the analysis of this thesis the best resolution achieved was 4.1%.

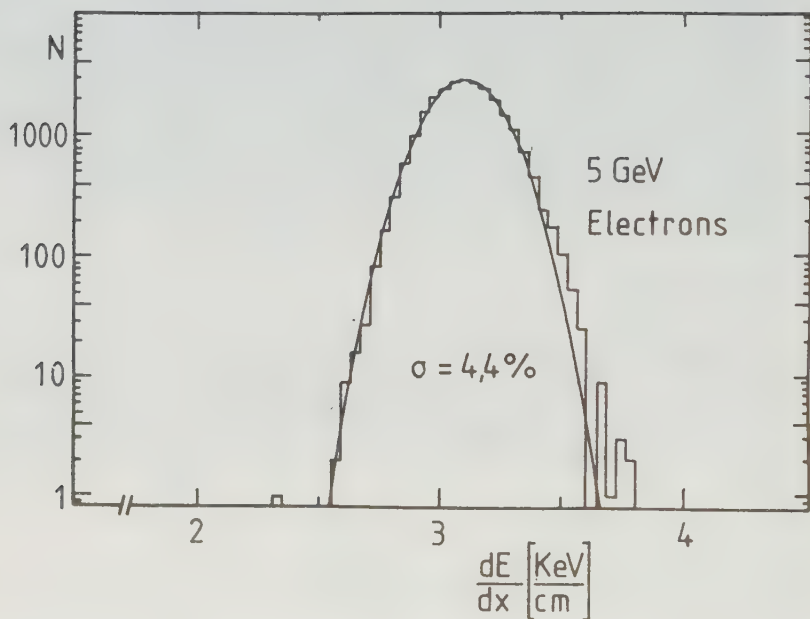


Figure 20. dE/dx for 5 GeV electrons

3. The long term stability

With a spacing of about 1 pb^{-1} in collected luminosity, small data samples were analysed to check the time dependence of the dE/dx resolution. The result is shown in Figure 21 on page 39 where the abscissa is labelled both with time information and information on the centre of mass energy. (1S, 2S and 4S corresponding to the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(4S)$ resonances and 'CON' to the non resonant or continuum regions). The average resolution is better than 5 % .

Assuming a dE/dx resolution of 5 %, the selectivity for different particle combinations is shown as a function of momentum in Figure 22, Figure 23 on page 41 and Figure 24 on page 41. $S = 1$ corresponds to a 3σ separation which, as shown in the figures, can be achieved for pions and kaons up to 0.8 GeV/c, for electrons and protons in the momentum regions < 1.0 GeV/c and > 1.7 GeV/c and for pions and protons in the regions < 1.3 GeV/c and > 3 GeV/c.

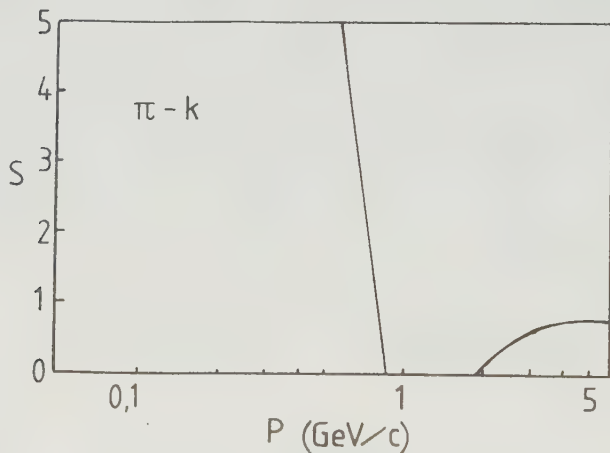


Figure 22. Particle selectivity for π -K

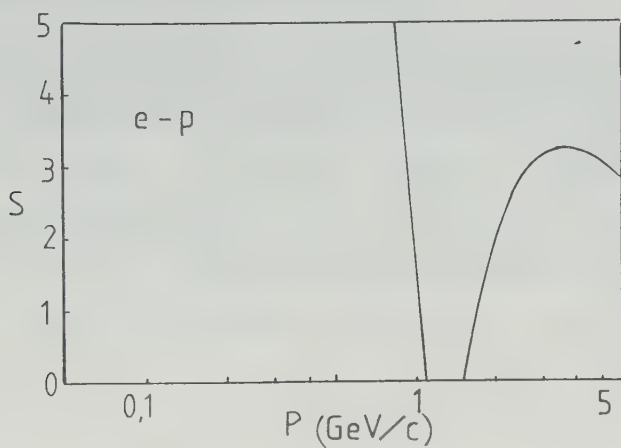


Figure 23. Particle selectivity for $e-p$

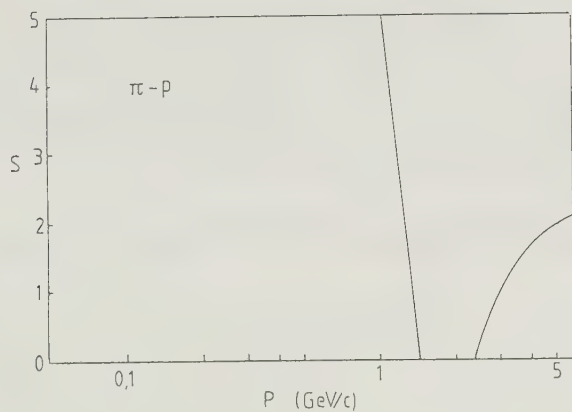


Figure 24. Particle selectivity for $\pi-p$

5. $\chi^2(dE/dx)$

For particle identification, a χ^2 value for each of the five (e, μ , π , K, p) hypotheses is calculated according to the expression below:

$$\chi^2(dE/dx) = (dE/dx(e) - dE/dx(t))^2 / (\sigma(p)^2 + \sigma(t)^2)$$

where $dE/dx(e)$ is the expected most probable energy loss and $dE/dx(t)$ is the truncated mean of the measured values. $dE/dx(e)$ can be calculated using the following formula (ref.6):

$$dE/dx(e) = \alpha t / \beta^2 \cdot [\ln(mc^2 \alpha t / I^2) \cdot 0.891 + 2 \ln \beta \gamma - \ln \beta^2 - \beta^2 - \delta]$$

with I : mean ionization potential

δ : density correction

αt : $0.153 Z/A \rho t$ (MeV for ρt in g/cm^2)

$\gamma = \sqrt{ (p^2 + M^2) } / M$

The error in the momentum determination translates into an error in dE/dx via the dE/dx -momentum relation and is given by $\sigma(p)$. $\sigma(t)$ is the error on the $dE/dx(t)$ defined as:

$$\sigma(t)^2 = 1/N(N-1) \cdot \sum_i (dE/dx(i) - dE/dx(t))^2$$

with N : the number of dE/dx samples.

$dE/dx(i)$: dE/dx sample i ($i = 1 \sim N$)

All the dE/dx quantities are normalized to an average track length (ATL) per cell because the most probable energy loss is not a linear function of the track length but is given by

$$E_1 = L_1/L_2 \cdot E_2 - a \cdot L_1/\beta \cdot \ln (L_2/L_1)$$

with $a = 0.1814$ keV/cm for the ARGUS drift chamber

where E_1 and E_2 are the most probable energy losses for the track lengths L_1 and L_2 . In the ARGUS analysis, L_1 is chosen to be the normalized track length and L_2 the actual track length in the drift cell, which makes the second term in the above expression negligible. This technique is important from a programming point of view because it reduces the number of operations and make the computation fast.

e. THE SPATIAL AND MOMENTUM RESOLUTIONS

In Figure 25 the spatial resolution, σ , for Bhabha electrons and in Figure 26 the spatial resolution, for hadron tracks are shown as a function of the distance from the sense wire.

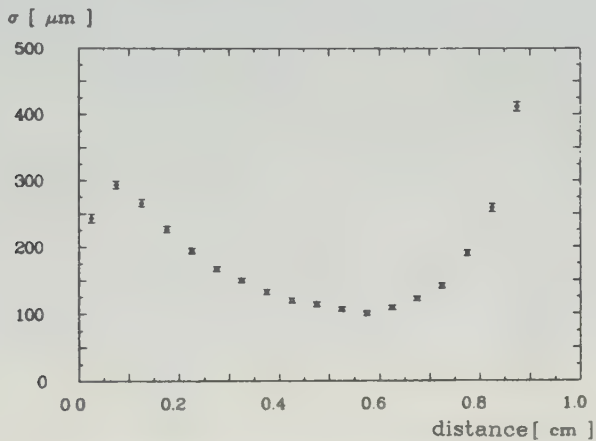


Figure 25. The spatial resolution for Bhabha electrons

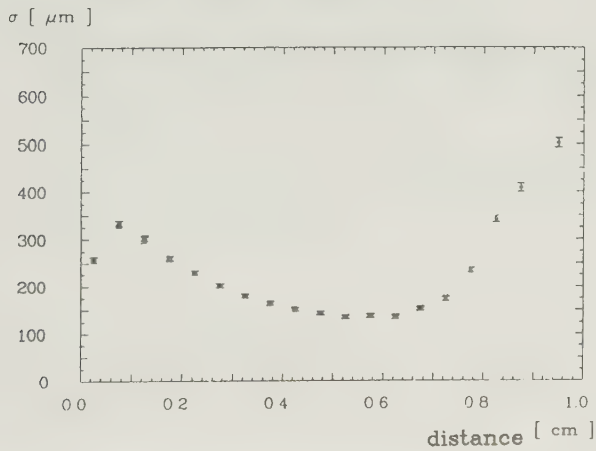


Figure 26. The spatial resolution for hadron tracks

As was discussed in section 2.3.3c the difference between the measured distance and the expected distance from the fitted track is called the residual. The standard deviation σ of the residual distribution is a measure of the spatial resolution. For large distances (≥ 0.8 cm) the resolution is worse than in the region $0.4 \sim 0.7$ cm, because the more complicated field structure at large distances (see Figure 12 on page 24). Thus the space-time relation becomes less well defined. Also, the increased diffusion of the electrons degrades the resolution. For very short distances ($\lesssim 0.1$ cm) the resolution also becomes worse because the drift distances of electrons from different parts of the track are very different in contrast to tracks at large distances. This is indicated in Figure 27 on page 45. For tracks at short distances the avalanches thus will not be produced at the same time which will cause the rise of the signal to be less sharp and correspondingly increases the uncertainty in the drift time measurement.

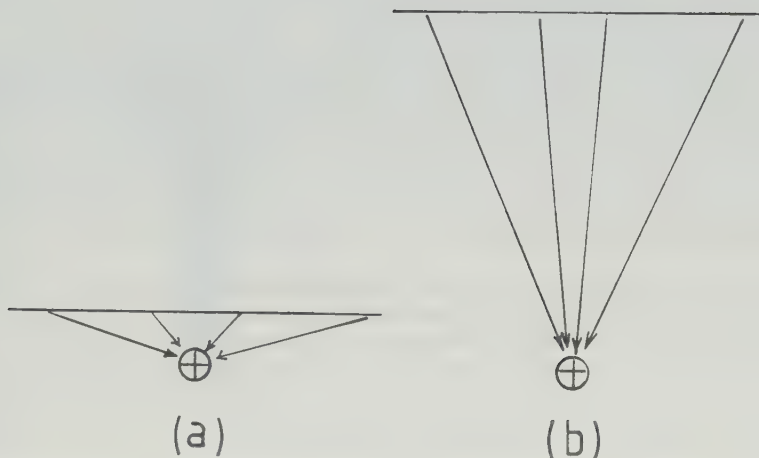


Figure 27. Drift distances from different points of the track:

(a) The distance between the track and the wire is small and the drift distances from different parts of the track are different.

(b) The distance between the track and the wire is large and the electrons from different parts of the track arrive almost at the same time.

Averaged over the whole drift cell σ is $189 \mu\text{m}$ for Bhabha scattered electrons and $217 \mu\text{m}$ for hadron tracks i.e. about 15 % larger for hadron tracks. This is mainly due to their smaller average momenta, which causes the influence of multiple scattering of the particle against gas molecules or wires to be larger and hence the residuals are larger.

The spatial resolution which is described above gives a momentum resolution according to the following expression:

$$\sigma/p = \sqrt{0.01^2 + 0.01^2 \cdot p^2}$$

with p in GeV/c²

2.3.4 The Time Of Flight (TOF) system

The Time Of Flight system consists of 64 barrel scintillation counters covering 75 % of 4π , and 2 x 48 endcap counters increasing the solid angle to 92 % of 4π . (Figure 5 on page 13). Each barrel counter is read out by two phototubes, while the endcap counters have one tube only. The TOF system serves as part of the fast trigger and is also used for identification of charged particles. The time resolution is 210 ps for Bahbha events, and 220 ps for hadrons, both in the barrel and endcap counters.

The flight time of a particle is extracted from the measured TDC values after application of a set of calibration constants, such as counter length, the effective speed of light inside the counter, delays due to the cable lengths e.t.c. The signal starting the TDCs is delivered by the DORIS bunch crossing signal and gated with the ARGUS trigger signal. The raw time values measured with the TDCs are also pulse hight corrected using the charge information obtained from the ADC units.

Figure 28 on page 47 shows a scatter plot of the particle mass squared versus its momentum. The mass squared M^2 is calculated by the following formula,

$$M^2 = p^2 \cdot (1/v^2 - 1/c^2)$$

where c is the velocity of the light, p and v are the momentum respectively the velocity of the particle. The momentum p is obtained from the measured bending radius in the magnetic field of the detector and the particle velocity v is obtained using the measured time-of-flight together with the track length information from the drift chamber. One sees that the particles are clearly separated up to certain momenta. A three standarder deviation mass separation is possible up to 700 MeV/c for pions and kaons and up to 1200 MeV/c for kaons and protons. Electrons can be separated from heavier particles up to 230 MeV/c.

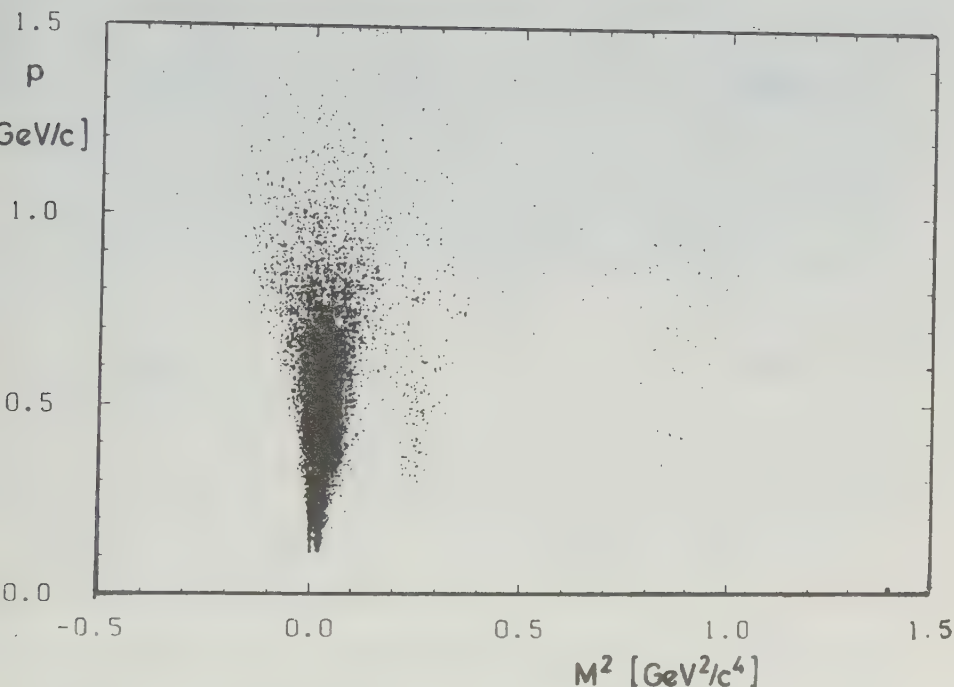


Figure 28. The momenta vs. M^2 for hadron tracks:

Only good quality tracks from the multihadron sample entered in this diagram.

The time resolution achieved for hadrons is demonstrated in Figure 29 on page 48. It shows the distribution of the difference between the time-of-flight expected from the track length and the measured time-of-flight for pions between momenta of 300 and 600 MeV/c . It follows a gaussian shape over more than a decade.

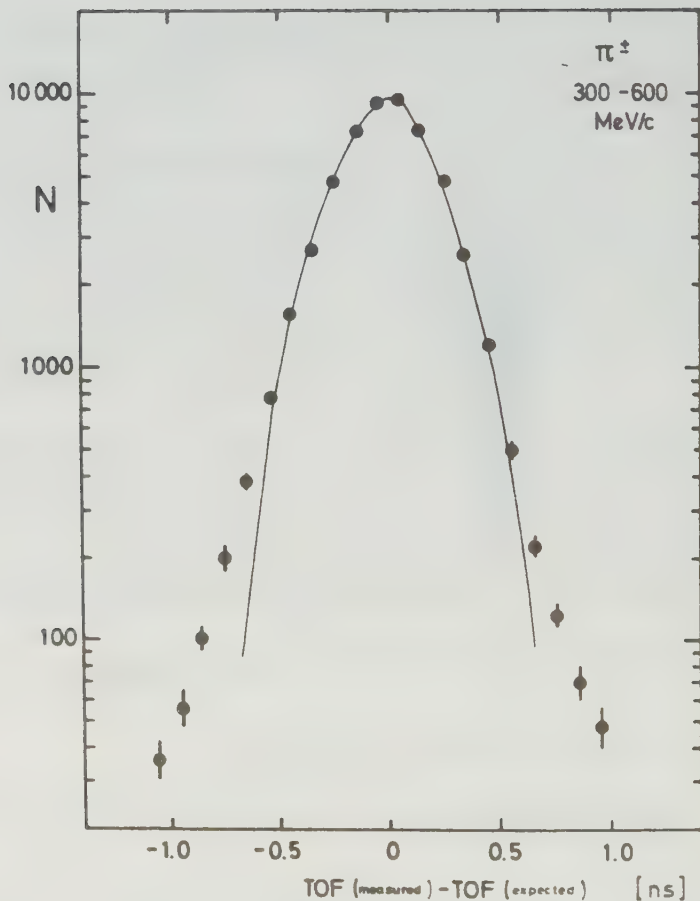


Figure 29. TOF(measured)-TOF(expected) for pions:

The distribution of the difference between the time-of-flight expected from the track length and the measured time-of-flight for pions between momenta 300 and 600 MeV/c.

Following the same method as for the particle identification by dE/dx -measurements, the time-of flight χ^2 values are calculated for five particle hypotheses (e , μ , π , K , p) in the following way:

$$\chi^2(\text{TOF}) = ((1/\beta(m) - 1/\beta(e))^2) / (\sigma(m)^2 + \sigma(e)^2)$$

where $\beta(m)$ is the measured particle velocity in units of the light velocity, $\beta(e)$ is the expected particle velocity from the track length, $\sigma(m)$ denotes the errors on $1/\beta(m)$, calculated from the TOF resolution and $\sigma(e)$ the error on $1/\beta(e)$, calculated from the momentum uncertainty. The χ^2 values from TOF and dE/dX measurements can be added for each particle hypotheses to obtain a more significant identification. Studying cases where $\chi^2(dE/dx)$ and $\chi^2(\text{TOF})$ are both less than 9, one finds a 97% agreement of for the kaon and the proton identification in the low momentum region.

2.3.5 The Shower counter system

The shower counter system consists of 1760 single shower counters. In the barrel there are 20 rings with 64 counters in each ring and the end caps have 240 counters each. The counter elements are of the sandwich type with interleaved plates of 1 mm lead and 5 mm scintillator. The total depth is 40 cm, corresponding to 12.5 radiation length, which is enough to completely absorb the produced showers in the energy range of interest. The solid angle coverage is 96 % of 4π .

The shower counter system is housed inside the coils which minimizes the amount of material between the interaction point and the shower counters. This allows sensitivity to photons down to ~ 50 MeV. The light emitted by particles reaches external photomultipliers through specially designed light guides passing between the magnet coils. The high granularity of the system provides good information on the impact point of the showering particle which allows the separation of adjacent showers. These properties are of prime importance for an efficient reconstruction of particles decaying into photons. The energy resolution has been measured to:

$$\sigma(E)/E \approx \sqrt{(0.07^2 + 0.08^2/E)}$$

with E in GeV and the angular resolution is

$$\sigma(\vartheta) \approx 11 \text{ mrad}$$

All counters are calibrated using Bhabha events and are continuously monitored with the help of a laser-pulse system.

2.3.6 The Muon chambers

The ARGUS detector is equipped with three layers of muon chambers (see Figure 5 on page 13). One layer is installed inside the magnet and covers 43 % of the full solid angle. A particle has to penetrate 3.3 absorption length of material to reach this layer from the interaction point. Two layers are outside the 1.8 absorption length thick magnet yoke and cover 87 % of the full solid angle. The absorbers serve as hadron filters to select muons, but lead to momentum cuts of about 700 MeV/c and 1100 MeV/c for muons detected by the inner and outer chambers respectively.

2.4 DATA

2.4.1 Trigger

The events are collected requiring at least one of the following three different triggers in coincidence with a bunch crossing signal of the DORIS II,

1. A total energy trigger, "E(tot)", defined by an energy deposit of > 800 MeV in each of the two z-hemispheres of the electromagnetic calorimeter.
2. A charged particle trigger, "CPT", requiring ≥ 3 tracks in the drift chamber, where each track is defined in two steps. A fast coincidence between groups of time of flight and shower counters and a slow coincidence using track masks in the drift chamber.

The shower counter information is used to require at least one track in one of the z-hemispheres.

3. "2 quasi-collinear tracks", basically the same as trigger 2, except that events with only two tracks are accepted if these tracks differ in azimuth by more than 120 deg.

Typical trigger rates are 4 Hz, at a luminosity of $10^{31}/(\text{cm}^2 \cdot \text{sec})$.

2.4.2 Multihadron events

Multihadron events were selected off-line by requiring more than or equal to four reconstructed tracks in the drift chamber with $|z_0|$ less than

8 cm and d_0 less than 1.5 cm, where z_0 is the z coordinate and d_0 is the distance in the transverse plane of the track's closest point to the z -axis.

2.4.3 Two prong events

The two prong events consist mainly of muon pairs, tau pairs and events from $\gamma\gamma$ reactions. These events are accepted, if they contain two oppositely charged tracks whose origin deviates from the interaction point by less than 6 cm in the beam direction and less than 1.5 cm radially or if at least one track has a momentum less than 2 GeV/c or the event has less than 0.6 GeV energy in the shower counters. In case the event fails the above selection criteria it is still accepted if at least one of the two tracks has a polar angle $|\cos\vartheta| < 0.866$ and in addition at least one of the following requirements to suppress Bhabha scattering events is fulfilled;

- at least one track with shower energy less than 1.5 GeV,
- at least one track with momentum less than 3 GeV and shower energy less than 4 GeV,
- the acollinearity between the two tracks larger than 15° ,
- the energy loss incompatible with an electron assignment, that is dE/dx less than 2 keV or dE/dx larger than 4.4 keV/cm.

3.0 SEARCH FOR FRACTIONALLY CHARGED PARTICLES

3.1 THE SEARCH

3.1.1 Data

The data used for this search are taken at various center of mass energies around 10 GeV, on and off the Υ resonances. The corresponding integrated luminosities and number of events used are listed below. Almost half of the data was taken on the $\Upsilon(2S)$ resonance ($\approx 10.023 \text{ GeV}/c^2$)

	L [pb^{-1}]	Selected Multihadron Events ($\times 10^3$)	Selected Two-prong Events ($\times 10^3$)
$\Upsilon(1S)$	23.6	321	278
$\Upsilon(2S)$	38.6	309	440
$\Upsilon(4S)$	10.0	53	65
Continuum	12.3	46	98
Total	84.5	729	881

3.1.2 The event selection

To suppress contributions from beam wall and beam gas interactions geometrical cuts were introduced to define the interaction region as a cylindrical volume with 2 cm radius and a length of 8 cm i.e.

$$\begin{aligned}\sqrt{(x_0^2 + y_0^2)} &\leq 2 \text{ cm and} \\ |z_0| &\leq 4 \text{ cm}\end{aligned}$$

where (x_0, y_0, z_0) is the closest point to the origin. Only particles in the barrel region (i.e. $|\cos\vartheta| \leq 0.7$ where ϑ is the polar angle) were considered to ensure good and consistent dE/dx measurements, TOF measurements and shower counter information. The χ^2 -probability for the track (see 2.3.3c) was required to be larger than 1 % to reject faked tracks.

The search was performed in two regions of energy loss and momentum which are not populated by the abundantly produced particles with charge one. For particles with charges other than one the apparent (measured) momentum has to be multiplied by the charge of the particle to get the true momentum. These regions are indicated by the hatched areas in Figure 30 on page 54.

In this plot approximately 1 % of the whole data sample is shown. Deuterons produced by beam gas interactions and other background tracks are not yet removed.

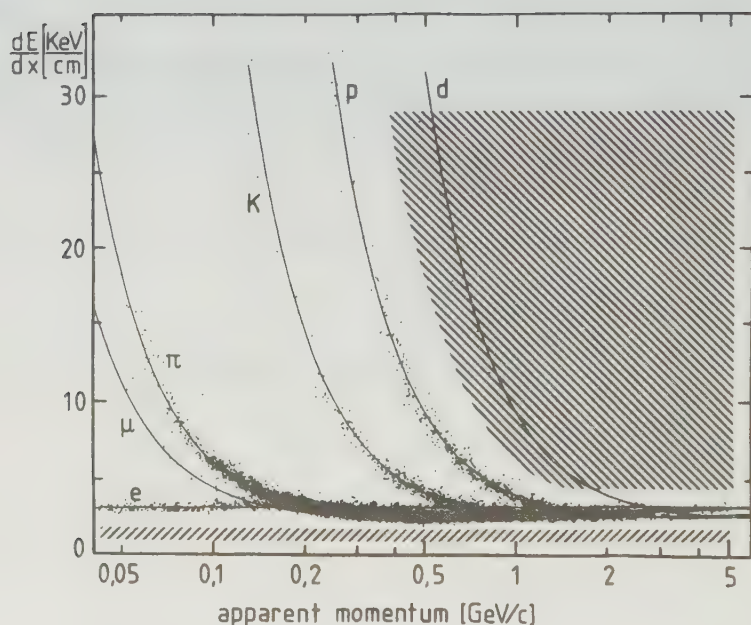


Figure 30. dE/dx vs. apparent momentum:

Regions in the dE/dx versus apparent momentum plane used in the search are indicated by the hatched areas.

(apparent momentum = momentum / charge). In this plot approximately 1 % of the whole data sample is shown. Deuterons produced by beam gas interactions and other background tracks are not yet removed.

In the upper dE/dx -region, the specific ionization was required to be larger than 4.0 keV/cm which corresponds to a separation of more than six standard deviations from the most probable energy loss of high momentum electrons. From acceptance considerations, which will be

described in section (3.3.1), this dE/dx -region was limited from above by a cut at 27.5 keV/cm. To exclude protons, kaons, pions and muons with low velocity, the dE/dx value was required to be larger than that expected for a unit charge particle with a mass of $1.41 \text{ GeV}/c^2$.

Also, a search in regions between the normally occurring particles should be possible and will be performed in the future. However, the dE/dx distributions for pions and muons are so close that the search in that region may not be possible.

In order to reject deuterons and tritons from beam gas and beam wall interactions, the charge of the particles was required to be negative. An analysis including both charge signs would have to rely on the fitted vertex point³ and the momentum balance⁴ in the event for this background rejection, which would be a source of some uncertainty. For this reason such a method was not used.

The number of dE/dx samples for each track was required to be larger than or equal to 15 after truncation in order to optimize the determination of energy loss and momentum.

The standard deviation of the specific energy loss distribution had to be less than 7 % for each track. This cut, supplemented by a requirement that the χ^2 probability for the track to be larger than 1% reject fake and overlapping tracks. One example of an event containing partially overlapping tracks is shown in Figure 31 on page 56.

³ A 'vertex fit' extrapolates fitted tracks in the drift chamber to the interaction region to estimate the origin of the tracks.

⁴ Beam-gas or beam-wall events arises from the collision of an electron or positron with a gas molecule or the vacuum pipe. In contrast to events from the electron positron collisions there is no momentum balanced in such an event.

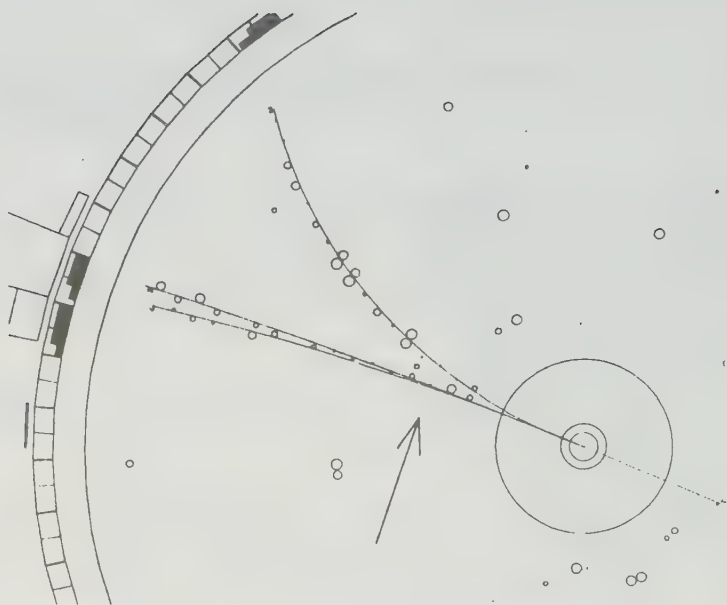


Figure 31. Partial overlap

The dE/dx value for each drift cell along one of the overlapping tracks is shown below. In the overlap region the dE/dx values are significantly higher which leads to an error on the specific ionization measurement $\sigma \approx 10\%$ for this track.

	Layer No.	dE/dx (keV/cm)	
The innermost layer	=> 1	19	
	2	15	
	3	18	
	4	10	
	5	13	Overlap
	6	11	
	7	12	
	8	13	
	9	32	
	10	31	
	11	10	
	12	8	
	13	---	<= not available
	14	---	
	15	---	
	16	11	
	17	8	
	18	7	
	19	---	
	20	---	Non overlap
	21	4	
	22	5	
	23	6	
	24	---	
	25	---	
	26	8	
	27	---	
	28	11	
	29	10	
	30	5	
	31	8	
	32	7	
	33	9	
	34	6	
The outermost layer	35	8	
	=> 36	--	

The limits of the lower dE/dx region (in Figure 30 on page 54) used for the search were $0.875 \text{ keV/cm} \leq dE/dx \leq 1.5 \text{ keV/cm}$. The upper boundary is $\sim$ six standard deviations away from the most probable energy loss of a minimum ionizing particle with unit charge. For particles with a specific ionization less than 0.875 keV/cm , the track reconstruction efficiency is low (< 0.7) and the behaviour of the detector is not well known.

In the lower dE/dx region there is neither any problem with overlapping tracks nor with contributions from beam gas or beam wall interactions, which would all give large dE/dx values. In this region there is thus no danger in also including positively charged particles. Another consequence is that the selection criteria didn't have to be as stringent as for the upper region: the number of dE/dx samples was required to be greater than 6 after truncation and the error on the specific ionization to be less than 18%.

3.2 THE RESULT OF THE SEARCH

After application of the above mentioned selection criteria no quark candidate was left in the lower search region. In the upper dE/dx region, the following events remained from the multihadron data and two prong data respectively.

3.2.1 Selected events from multihadron data

From the multihadron sample, sixteen events remained which could be divided into three types.

a. Type 1

A typical event of "type 1" and its dE/dx plot are shown in Figure 32 on page 59 and Figure 33 on page 60 respectively.

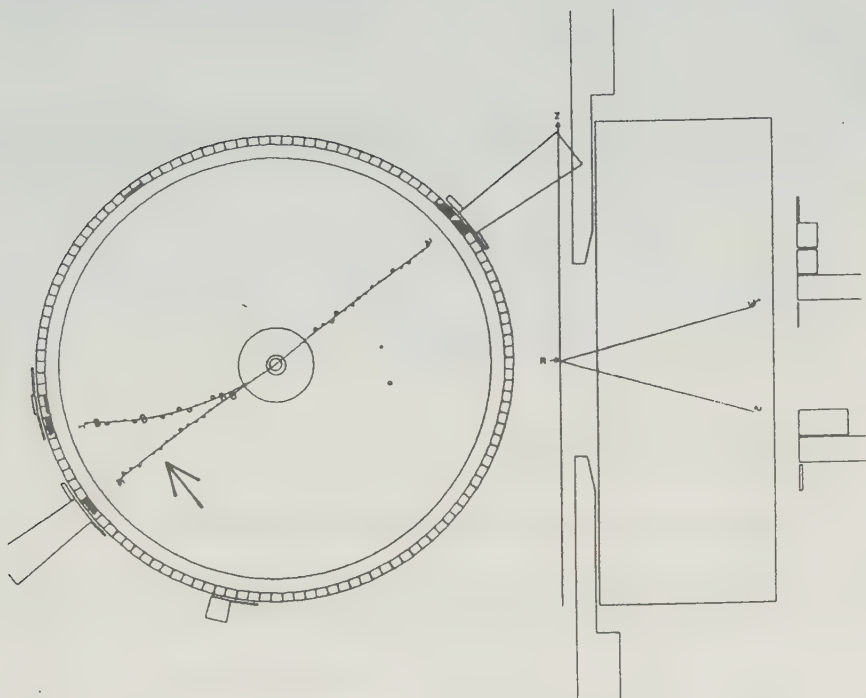


Figure 32. A typical event of "type 1":
 x - y and ρ - z projection.

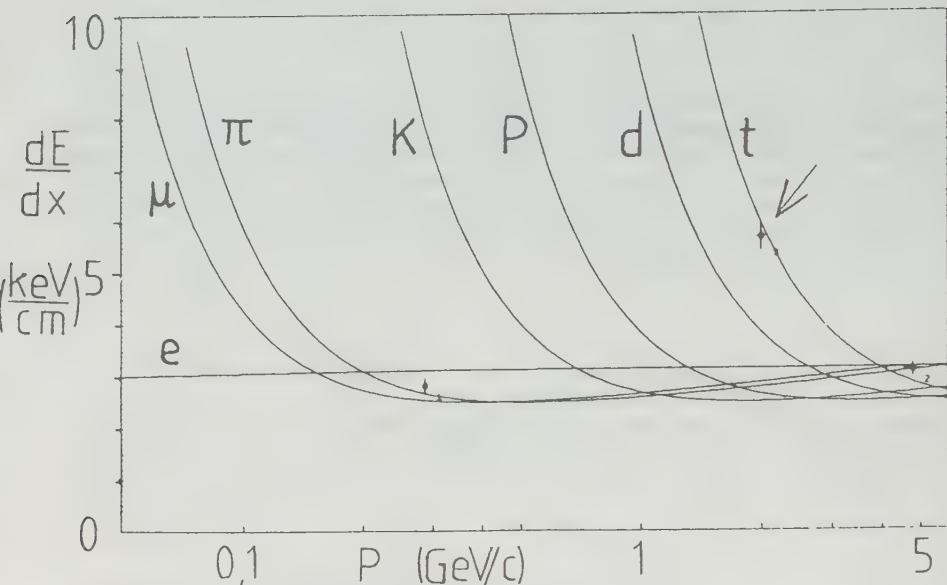


Figure 33. The dE/dx display of "type 1" event

These events contain tracks with the following characteristics:

- The energy loss of the track is twice that expected for an electron with the same momentum and when plotted in the dE/dx vs. p plane they fall on a line parallel to the electron line.
- Charge conservation demands an additional track with the same charge as the candidate track.
- The time of flight measurement is consistent with $\beta = 1$.
- The energy deposited in the shower counters corresponds to twice the momentum of the track, and the shape of the energy distribution in the shower counter system (cluster shape) is consistent with the electron hypothesis.
- Momentum balance demands another track with approximately the same momentum as the candidate track at the same position.

When one removes the cut on the dE/dx resolution one gets more events of this type with partially resolved electron tracks. Therefore these

nine events can be explained as containing overlapping tracks of electrons originating from radiative Bhabha scattering events, where the radiated photon converts into an electron positron pair before reaching the drift chamber volume, i.e. $e^+e^- \rightarrow e^+e^-\gamma$ followed by $\gamma \rightarrow e^+e^-$. Since normally the radiated photon proceeds in the same direction as the parent electron, an overlap can happen much more easily for Bhabha scattering events than for multihadron events.

b. Type 2

These 6 events contained clearly identified antideutrons, the analysis of which will be discussed in more detail in chapter 4.

c. Type 3

The remaining one event is shown in Figure 34 on page 62.

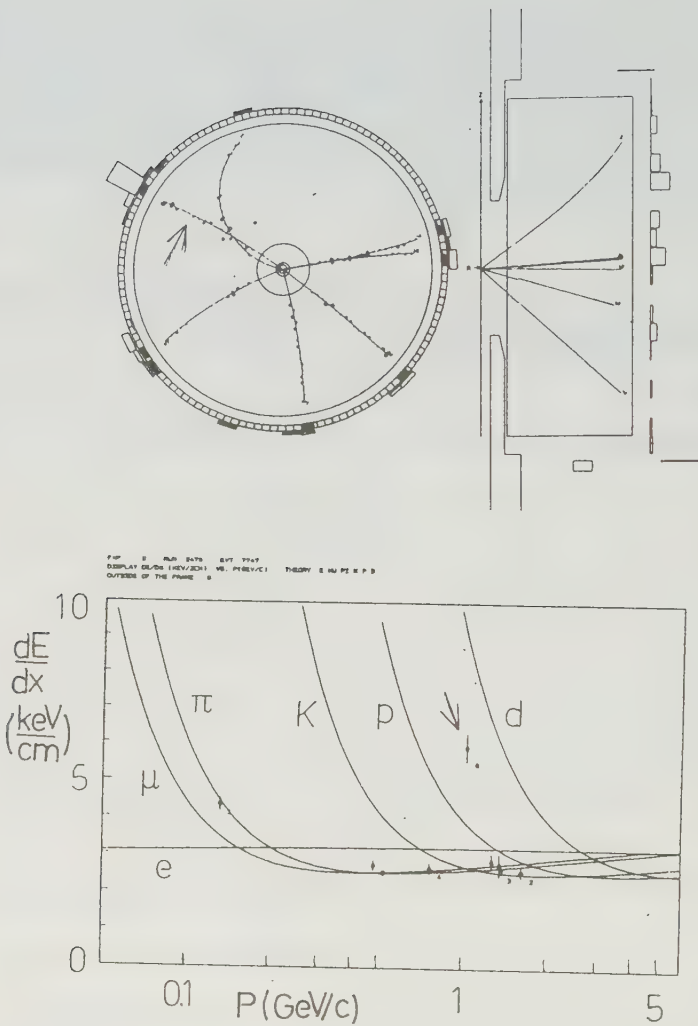


Figure 34. The "type 3" event:

The event display (x - y and p - z projection) and the dE/dx display of the "type 3" event

The "type 3" event contain a track which is characterized by:

- The energy loss is approximately twice that expected for an pion.
- Charge conservation demands an additional track with the same charge as the candidate track.
- The time of flight measurement is consistent with the fast pion hypothesis.
- The energy deposited in the shower counter system and the cluster shape are consistent with it being a hadron.
- The missing P_T , considering both charged tracks and photons, coincide with the P_T of the track: $\Delta\Phi = 0.04$, $\Delta P_T = 0.24 \text{ GeV}/c$

The possibility that the track is from a particle with charge -2 could be excluded since the specific ionization then has to be at least four times as large as that of a minimum ionizing particle (dE/dx is proportional to the charge squared) and this is in contradiction to the observed dE/dx value. Therefore this track is explained as two overlapping hadrons.

The table below shows how these event types were distributed among the resonances and continuum data used in the analysis.

	Type 1	Type 2	Type 3
$\Upsilon(1S)$	6	2	0
$\Upsilon(2S)$	1	3	1
$\Upsilon(4S)$	2	1	0
Continuum	0	0	0
Total	9	6	1

3.2.2 Selected events from two prong data

In two prong data the following 9 events were left.

	Type 1
$\Upsilon(1S)$	1
$\Upsilon(2S)$	7
$\Upsilon(4S)$	1
Continuum	0
Total	9

These events all contain tracks with the same characteristics as the "type 1" events in the multihadron data. The only difference is that the $\gamma \rightarrow e^+e^-$ conversion occurs in the drift chamber inner wall in contrast to the multihadron events where the conversion normally occurs much earlier. Low momentum electrons from late conversions are not reconstructed to the main vertex and consequently these events are found in the two prong data.

Thus for all tracks fulfilling the selection criteria an explanation could be found and therefore

WE CONCLUDE THAT NO EXOTIC PARTICLES HAVE BEEN OBSERVED

3.3 EFFICIENCIES

The detection efficiency, ε , is a function of momentum, charge, mass and the specific ionization of the track. It was determined separately for the upper and lower regions since the selection criteria were very much different for these.

In the process of determining the various efficiencies necessary for the quantization of our results, Monte Carlo generated events from the SIMARG program package were used. SIMARG (SIMulation of the ARGus detector) was developed using the general program package GEANT (Generation of Events ANd Tracks) from CERN (ref. 30). The generated tracks in the event are subject to multiple scattering and energy loss and the program delivers kinematical quantities as well as detector signals such as hit wires, drift times and energy deposited per drift cell.

3.3.1 The efficiency in the upper region

The track reconstruction efficiency was determined from a scan by eye of a few hundred events, that is some thousand tracks, from different data taking periods and was found to be 0.977 in average. The effect of the cut on the closest point to the origin was obtained using Monte Carlo generated events by applying the same cuts as for the data. The inefficiency due to this cut was 0.1%. With the assumption of a flat angular distribution the requirement that only particles in the barrel region are accepted ($\cos \vartheta < 0.7$) gives an efficiency of 0.7. The trigger efficiency varies between 0.7 and 0.95. The lower limit of the trigger efficiency was determined from the μ -pair trigger efficiency for $\cos \vartheta < 0.7$. For the multiprong events the efficiency is higher. The efficiency of the σ -cut on dE/dx of less than 7% was determined to be 0.985 from the σ distribution for low momentum (i.e.

highly ionizing) particles. The influence of the cut on the number of dE/dx measurements per track was also obtained from highly ionizing particles and is shown in Figure 35 as a function of dE/dx . For large dE/dx values the efficiency drops due to ADC overflow, hence the cut at 27.5 keV/cm.

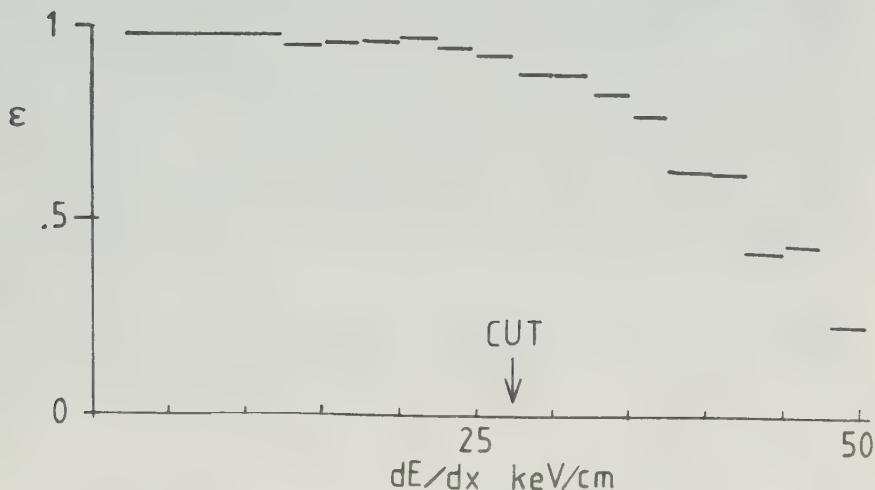


Figure 35. The acceptance vs. dE/dx :

The acceptance of the cut on the numbers of dE/dx samples as a function of the dE/dx which was obtained using the highly ionizing particles.

The efficiency of the cut on the χ^2 probability for the track ($\text{prob}(\chi^2) \geq 0.01$) was obtained from the $\text{prob}(\chi^2)$ distributions (see 2.3.3c) at several data taking periods and was 0.87 on the average. Losses due to absorption in the beam tube and in the inner wall of the drift chamber can be neglected if one assumes that the absorption length for a fractionally charged particle is of the same order as for a pion. In ARGUS a particle traverses

only 1.2% of a nuclear interaction length before being detected in the drift chamber. Multiplying all these efficiencies gives the total efficiency ϵ .

3.3.2 The efficiency in the lower region

The track reconstruction efficiency as a function of dE/dx was determined by the same method as in the upper region using data taken with reduced high voltage in the drift chamber. It reduces linearly from 0.9 to 0.7 as the dE/dx of the track decreases. The geometrical cut on the interaction region gives the same efficiency as in the upper region. The trigger efficiency was estimated using Monte Carlo and was found to vary from 0.7 to 0.4 for multihadron events. To obtain the trigger efficiency which is rather insensitive to specific assumptions about the quark production mechanism, we made the following Monte Carlo study. Events were generated for the process $e^+e^- \rightarrow c\bar{c}$ and then fragmented according to the Field and Feynman model (ref.46). After the fragmentation, charmed mesons were not allowed to decay and were considered as non interacting particles to model the worst scenario for free quarks. The trigger efficiency was then obtained as a function of the total energy of the remaining hadrons. Because the trigger efficiency for low multiplicity events is very low and cannot be well determined in this region, they were not included in the search. In the lower region the cuts on the number of samples (≥ 7) and on $\sigma(dE/dx)$ ($< 18\%$) are so loose that the losses due to these cuts can be neglected ($\lesssim 10^{-6}$). Due to the low primary ionization the dE/dx resolution becomes worse for the lower region (approximately 11 % on the average) compared to the upper region (approximately 5 % on the average). This deterioration in resolution affects the detection efficiency. As for the upper region the total efficiency, ϵ , is obtained as the product of all above discussed efficiencies. Both charges are considered which gives a factor of two larger sample compared to the upper region.

3.4 FINAL RESULTS

The result that no unusually ionizing particles were observed in this search was converted into upper limits for free quark and free di-quark production cross sections.

From the definition of the integrated luminosity L_1 (see 2.2) the expected number of events, N , is given by:

$$N = \sum_i L_1(i) \cdot \sigma(q)$$

Since no events were observed, Poisson statistics gives an upper limit of 2.3 for N with 90% confidence. The sum is extended over the various beam energies, where the integrated luminosities, $L_i(i)$, were accumulated. $\sigma(\text{vis})$ is the visible quark cross section which is related to the true cross section, σ , by

$$\sigma(\text{vis}) = \int d\sigma/dp \cdot \varepsilon dp.$$

where ε is the efficiency which has been discussed in the previous sections. The integral was performed for a fixed quark mass and charge. The following two assumption for the momentum distribution of the quarks were made:

$$(1) \sim P^2 / E$$

$$(2) \sim P^2 / E * \exp(-3.5E)$$

with P and E in GeV/c and GeV/c² respectively

(2) is the distribution observed for pions, kaons, and protons in electron positron annihilation (ref.31). As an extreme case the momentum distribution (2) was also considered, as previously suggested by the JADE collaboration (ref.18).

The results are presented as a ratio to the muon production cross section, $R(q)$, and are shown in Figure 36 on page 68. In the case of $Q=2/3$ or $=4/3$, the limits can be extended to quark masses of zero.

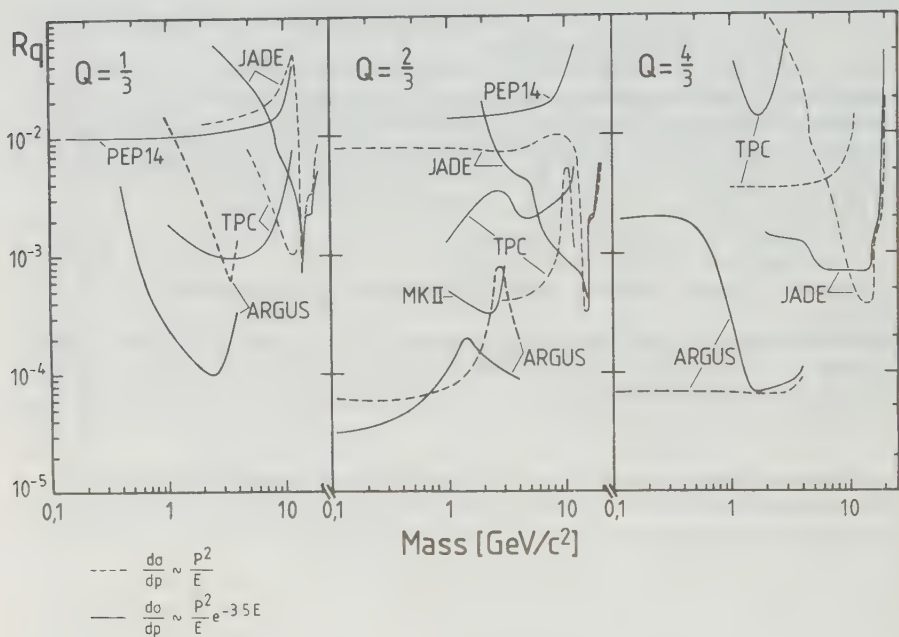


Figure 36. $R(q)$ upper limits at the 90 % confidence level:

$$R(q) = (e^+e^- \rightarrow qX) / (e^+e^- \rightarrow \mu^+\mu^-)$$

4.0 THE FIRST OBSERVATION OF ANTIDEUTERON PRODUCTION IN ELECTRON POSITRON ANNIHILATION .

4.1 THE SEARCH

See the previous chapter.

4.2 ANTIDEUTERON CANDIDATES

4.2.1 The evidence

From the dE/dx analysis discussed in the previous chapter there are six events containing antideuteron candidates (see 3.2). For these events the following items were checked to verify their identification as antideuterons. The setting of the magnetic field was verified by not only checking the hardware setting but also by using the angular distribution of Bhabha scattered electrons from the runs where the antideuteron candidates were observed. For each drift cell the raw ADC values and the applied corrections to deduce the dE/dx for the actual track (see 2.3.3d) were checked. The behaviour of the the time-of-flight counters and the shower counters were checked for these runs. For example the consistency of the phototube information from both sides of the TOF-counters was checked.

a. The dE/dx INFORMATION

In Figure 37 on page 70 the energy loss as a function of momentum is shown for approximately 1 % of the total data sample, including deuterons from beam gas or beam wall interactions. On top of this the six antideuteron candidates have been included.

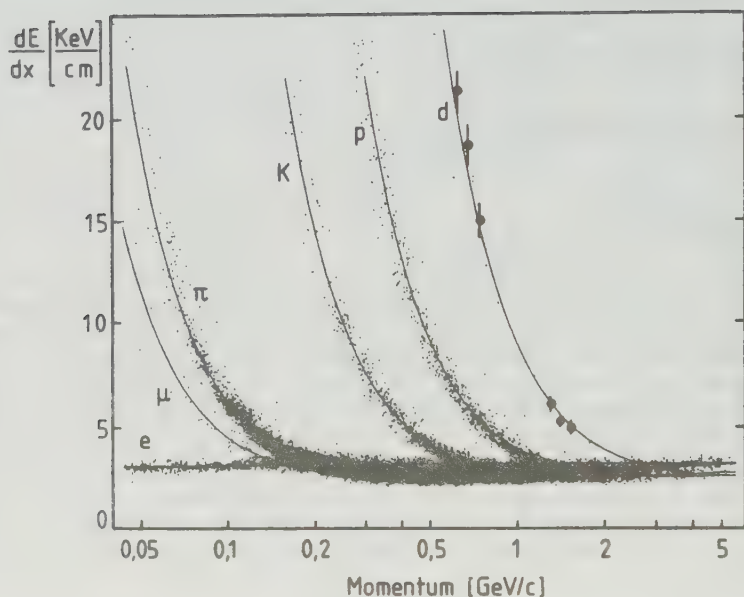


Figure 37. Six antideuteron candidates:

Energy loss as a function of momentum is shown for approximately 1 % of the total data sample i.e. deuterons from the beam gas or beam wall interactions are also present. On top of this the six antideuteron candidates have been included.

The observed energy losses are in good agreement with that expected for antideuterons.

b. THE TOF INFORMATION

For all six candidates the time of flight information was compatible with the antideuteron assignment.

In three cases the mass determination was possible.

The first observation of antideuteron production in electron positron annihilation .

	Mass (GeV/c^2)
(1)	1.86 ± 0.07
(2)	1.99 ± 0.13
(3)	1.86 ± 0.12

For two cases the candidate annihilated in the front part of the shower counter, which caused back scattering of particles produced by the annihilation into the TOF counters and the drift chamber. The many hits in the TOF-counters disturbed the pulse height measurement and thus prevented the mass determination. In one case an unusually large pulse prevented a reliable mass determination. However in all these three cases, the time of flight information (TDC value) indicated very slow particles which together with the large pulse (ADC value) and observed backscatter from the annihilation, support the antideuteron assignment. Figure 38 on page 72 shows one of the events where the antideuteron is absorbed, causing a pronounced albedo. The antideuteron candidate, its albedo and two proton candidates are labelled.

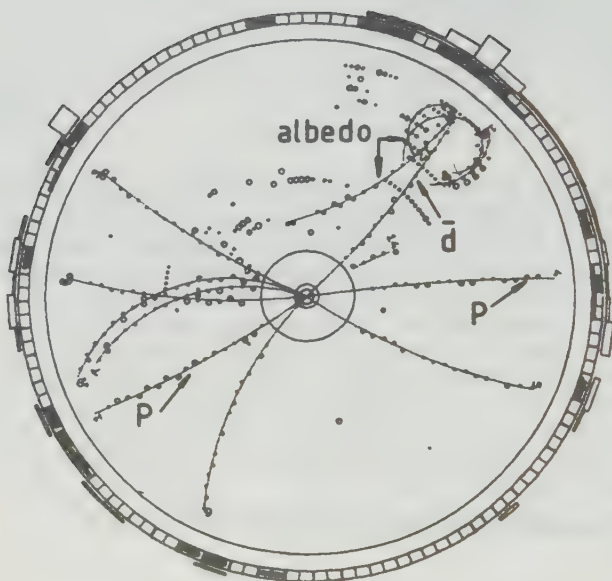


Figure 38. One of the events with an antideuteron candidate track:

The antideuteron candidate, its albedo and two proton candidates are labelled.

c. THE SHOWER COUNTER INFORMATION

For each of the six antideuteron candidates the shower counter information was compatible with what was expected. All six particles populate the region of high energy loss and large cluster size in the shower counter, which is expected for antideuteron, but not for normal hadrons. Figure 39 on page 73 shows the cluster size, defined as the number of neighbouring shower counters set, as a function of the energy deposition, E , and Figure 40 on page 74 gives the projection on the E axis.

- . : Normal hadron tracks
- o : antideuteron candidates tracks

The first observation of antideuteron production in electron positron annihilation .

The smaller energy deposition for three of the antideuteron candidates is due to the backscattering process, where only part of the incoming particle energy is absorbed in the shower counter.

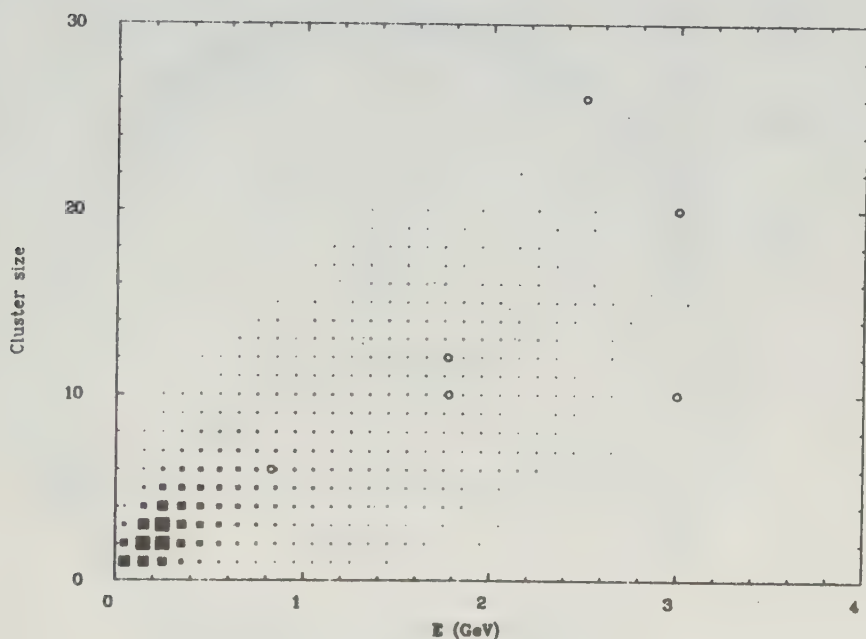


Figure 39. Cluster size vs. shower counter energy

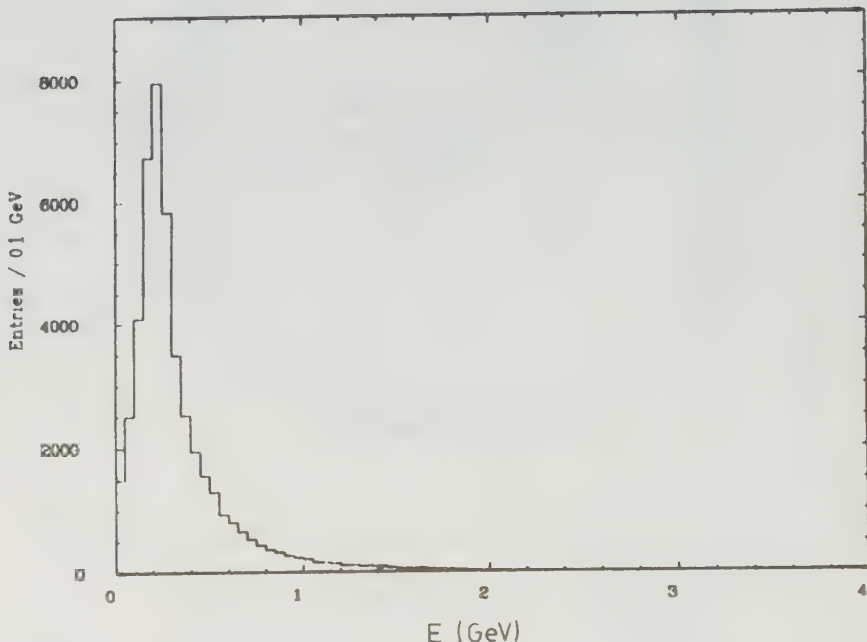


Figure 40. The projection of the last figure on the E axis

d. THE PROTON

In each of the six events, at least one proton candidate track was detected. This should be compared with the measured production rate of about 0.2 (anti)protons per hadronic event in electron positron annihilation at $\sqrt{s} = 10$ GeV. This high proton production rate can easily be explained by baryon number conservation, if the candidate tracks are antideuterons. In other words, the observed high proton rate also supports the antideuteron assignment.

The first observation of antideuteron production in electron positron annihilation .

4.2.2 Examples

Three of the events with an antideuteron candidate track are shown below. (Figure 41, Figure 42 on page 76, Figure 43 on page 77) The antideuteron candidate, its albedo and the proton candidate are labelled.

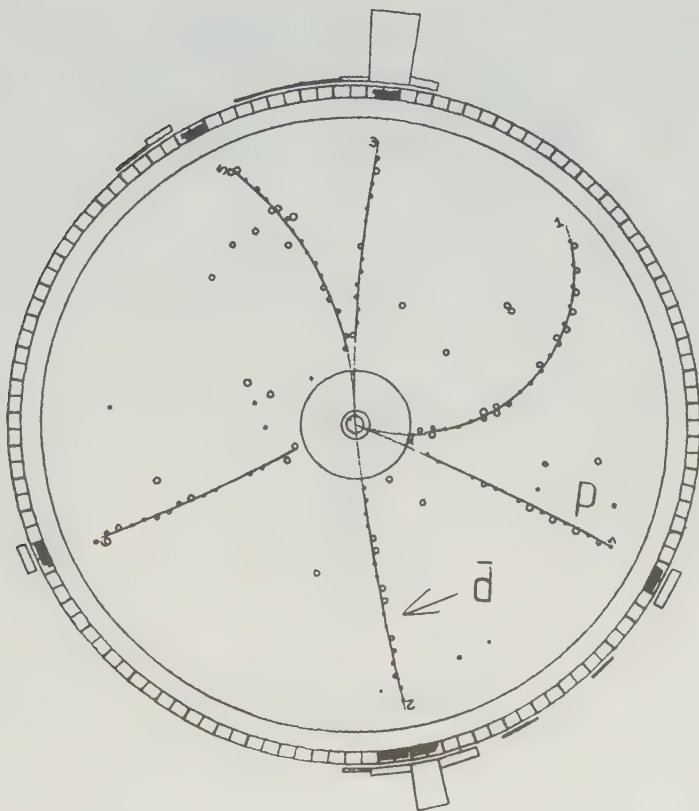


Figure 41. One of the events with an antideuteron candidate track
(a)

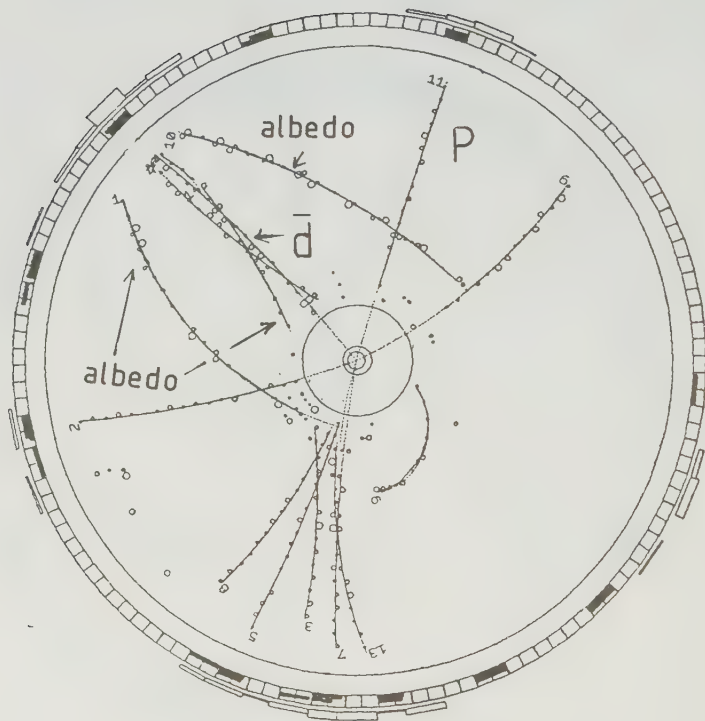


Figure 42. One of the events with an antideuteron candidate track (b)

The first observation of antideuteron production in electron positron annihilation .

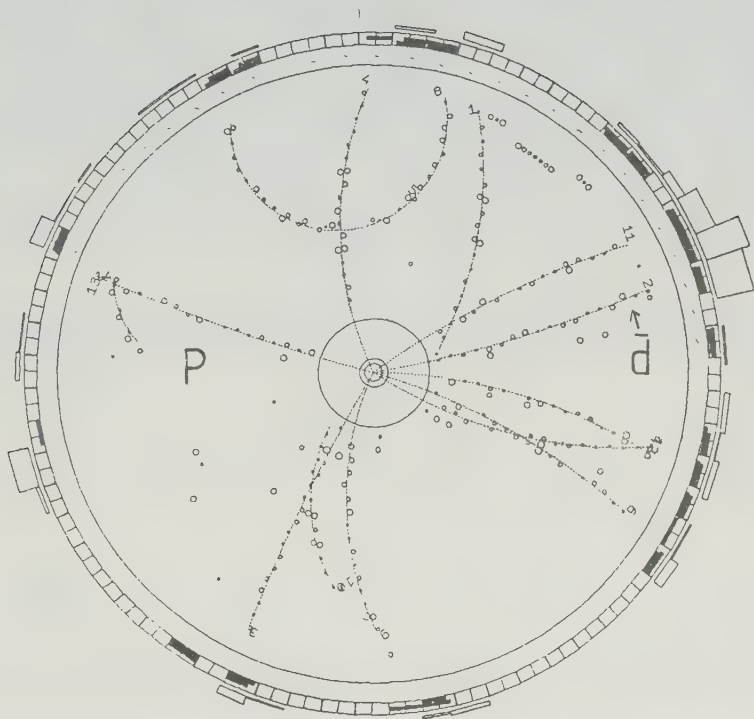


Figure 43. One of the events with an antideuteron candidate track (c)

The first observation of antideuteron production in electron positron annihilation .

4.3 RESULTS AND DISCUSSION

4.3.1 Lorentz invariant cross section

To obtain the cross section for antideuteron production the efficiency of the search has to be known. The reconstruction efficiency and the effect of the cuts applied for the search were already described in (3.3.1). The antideuterons have to pass through some material before being detected in the drift chamber. The beam pipe and the drift chamber inner wall correspond to 1.107 % of a nuclear interaction length, but 30 % of the data were taken with an additional copper foil around the beam pipe and a vertex drift chamber installed between the beam pipe and the main drift chamber. Together these increased the amount of material to 1.377 % of a nuclear interaction length. In the energy range of the observed antideuterons , 1.97 to 2.60 GeV/c², the absorption varies from 7.5 % to 5.5 % as given by the cross section data in ref. 33. The overall antideuteron detection efficiency was ~ 0.55 .

The Lorentz invariant cross section for the production of antideuterons was calculated in two energy bins and the result is shown in the following table.

$E(\bar{d})(\text{GeV})$	$E \, d^3\sigma/d^3p \, (10^{-5}\text{nb/GeV}^2)$
1.97 $\sim$ 2.29	3.1 (+ 3.0, -1.7)
2.29 $\sim$ 2.60	2.0 (+ 2.0, -1.0)

In Figure 44 on page 79 the result is compared to the production cross section for pions, kaons and twice that for antiprotons. The cross section for antideuterons is suppressed by two orders of magnitudes. This is an indication that the production mechanism of deuterons in electron positron annihilation is different from that of pions, kaons and protons.

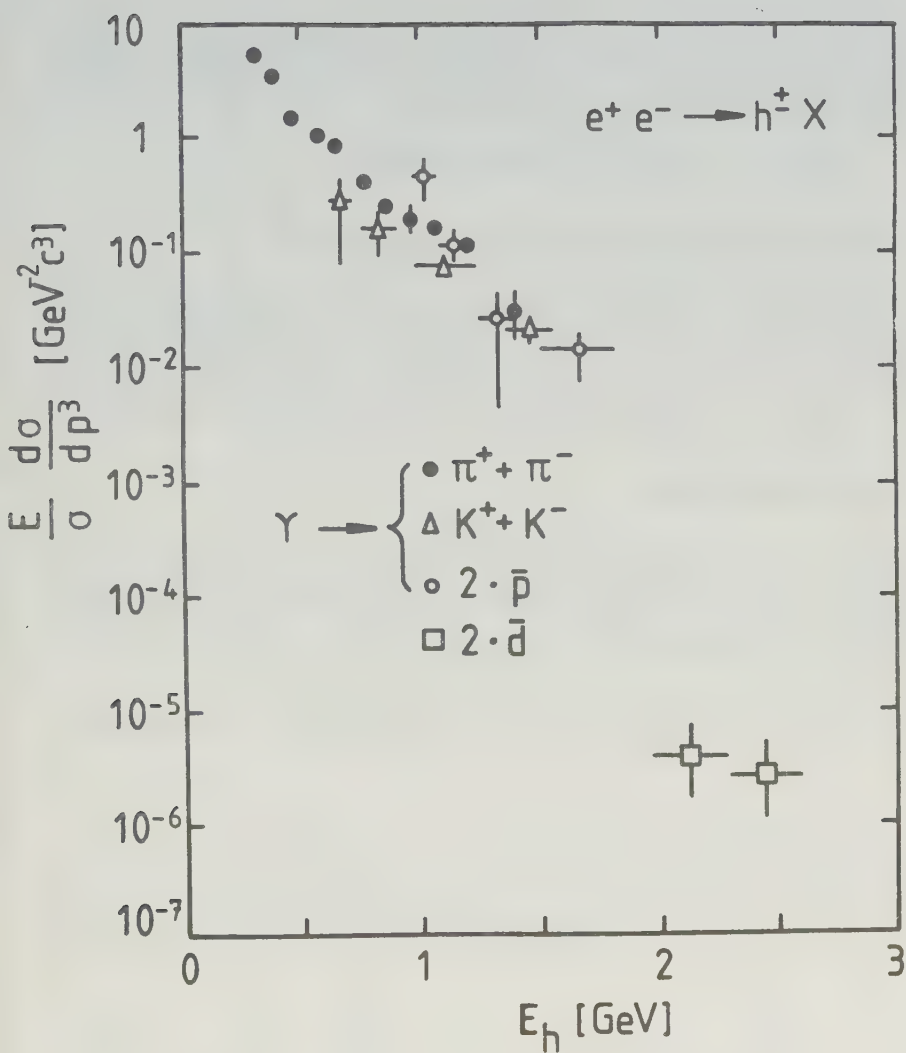


Figure 44. Lorentz invariant cross section for $\bar{d}$ production

The first observation of antideuteron production in electron positron annihilation .

From the overall antideuteron detection efficiency (0.55), the number of hadronic events used in the search ($729 \cdot 10^3$), and the number of observed events (6), the production rate for antideuterons in the energy range $1.97 \text{ GeV} \sim 2.6 \text{ GeV}$ is calculated to be:

$$\left[1.6 (+ 1.0, - 0.7) \right] 10^{-5} \text{ 1/hadronic event}$$

4.3.2 Characteristics of the events with antideuteron

Although the antideuteron sample is small, no differences between these events and other hadronic events were observed including mean charge multiplicity or event shapes measured by sphericity, thrust and aplanarity. The only difference observed is the high proton production rate, which is a natural consequence of the baryon number conservation.

4.3.3 Baryon correlation

Since there is at least one proton candidate track in each event containing an antideuteron, the angular correlation of the baryons was studied. Figure 45 on page 81 shows the number of combinations⁵ versus $\cos \alpha$, where α is the angle between the proton and antideuteron candidates in the detector frame.

No conclusion can be drawn, but it is interesting to see that there are protons going in the same direction as the antideuteron.

⁵ An event with two proton candidates gives two entries.

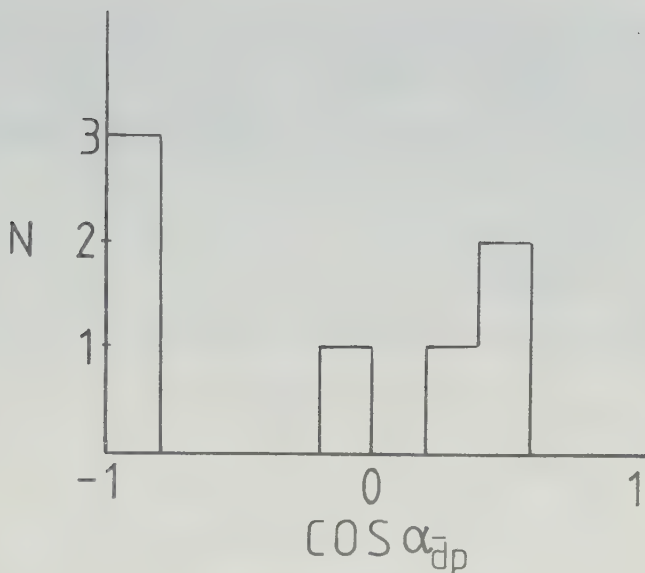


Figure 45. The number of combinations vs. $\cos \alpha$:

α is the angle between the proton and antideuteron candidates in the detector frame.

4.3.4 Discussions

With the limited statistics of 6 antideuterons, it is not possible to decide whether they come primarily from a three gluon decay or from continuum production. However the number of events with an antideuteron from the different data samples looks proportional to the collected integrated luminosities " L_1 ", as is evident from the following table.

	$\bar{d}$	$L_1 \text{ pb}^{-1}$
T(1S)	2	23.6
T(2S)	3	38.6
T(4S)	1	10.0
Continuum	0	12.3
Total	6	84.5

The first observation of antideuteron production in electron positron annihilation .

Previously, antideuteron production has been observed in proton nucleon interactions, e.g. at the CERN PS (ref.34), the AGS (ref.2), at Serpukhov (ref.35,36), NAL (ref.37,38) and the ISR (ref.39). All these data, which were taken in a broad interval of center of mass energies, can be related by a scaling law for the ratio

$$r = \frac{N(\bar{d})/N(\pi^-)}{N(\bar{p})/N(\pi^-)^2}$$

The table below gives the results for particle production ratio r from these experiments (ref.1) :

P(inc) (GeV/c)	30	43	70	300	1500
Target	Be	Al	Al	W	P
r (10^{-3})	1.5	2.4	3.4	10.0	5.0
ref.	2	35	36	37	39

The energy independent value of r was interpreted semiquantitatively in a model by Dorfman et al. (ref.2) as the production of two independent antinucleons which might form an antideuteron if they are produced close in phase space and have small enough relative momenta.

The ratio r obtained in this experiment is:

$$r \sim 2 \cdot 10^{-3}$$

It is in the same order of magnitude as observed in proton nucleon interactions which on the average is:

$$r \sim 5 \cdot 10^{-3}$$

It is tempting to generalize this model to antideuteron production in electron positron annihilation.

The first observation of antideuteron production in electron positron annihilation .

5.0 THE APPLICATION OF THE DE/DX MEASUREMENTS TO THE CHARM PHYSICS

5.1 PRODUCTION AND DECAY OF THE CHARGED D* MESON

Because of their short life times, the charged D* and D meson cannot be detected directly in the drift chamber. One can establish their production in the invariant mass distribution for the final states. In the identification of the charged D* meson we have taken advantage of the low Q-value (5.8 MeV) of the decay $D^{*+} \rightarrow D^0\pi$ (the explicit reference to charge conjugate states is omitted), which gives a well defined mass difference $\Delta M = M(D^0\pi^+) - M(D^0)$, and allows the cascade decay events to be seen in the presence of large combinatorial background.

The following decay channels were studied.

$$\begin{aligned} D^{*+} &\rightarrow D^0\pi \\ &\text{where} \\ D^0 &\rightarrow K^-\pi^+ & (5.1-1) \\ &\text{and} \\ D^0 &\rightarrow K^-\pi^+\pi^+\pi^- & (5.1-2) \end{aligned}$$

For each track which was detected by the ARGUS detector a χ^2 for each mass hypothesis (π , K or p) was calculated by adding the corresponding χ^2 values for the dE/dx and the TOF measurements which were obtained by the methods described in chapter 2. The normalized probability for each mass hypothesis is then:

$$P_i = \exp(-\chi_i^2) / \sum_j \exp(-\chi_j^2/2) \quad (5.1-3)$$

$i, j = \pi, K \text{ and } p.$

A track is considered as a candidate for each mass hypothesis which gives "an acceptable probability". The definition of "an acceptable probability" is not trivial. A stringent cut on the mass hypothesis probability will reduce the background but also the signal.

In calculating the invariant masses, tracks giving an acceptable probability enter into several mass combinations with equal weight. By a very loose cut of " $P > 0.01$ ", which reduces the background considerably while losing only a negligible amount of the signal, all invariant mass combinations were formed. The mass difference distributions for $M(K^-\pi^+\pi^+) - M(K^-\pi^+\pi^+\pi^-)$ yielded the mass difference $M(D^{*+}) - M(D^0) = (145.46 \pm 0.07 \pm 0.03)$ MeV which is considerably more precise than the world average (ref.33).

Fitting the invariant mass distribution for $K^-\pi^+$ and $K^-\pi^+\pi^+\pi^-$ with a gaussian line shape, upon a third order polynomial background gives 191 ± 19 events and 216 ± 21 events respectively in two peaks. Correcting for acceptance obtained by Monte Carlo simulation, the relative branching ratio of the two channels was calculated to $\text{Br}(D^0 \rightarrow K^-\pi^+\pi^+\pi^-) / \text{Br}(D^0 \rightarrow K^-\pi^+) = 2.17 \pm 0.28 \pm 0.23$

From the number of D^{*+} events as a function of x_p , where $x_p = P(D^*) / P(\text{max})$ with $P(\text{max}) = \sqrt{(E(\text{beam})^2 - M(D^*)^2)}$, $s \cdot d\sigma/dx_p$ was calculated and compared to two models, that of Peterson et al. (ref.42) where

$$s \cdot d\sigma/dx_p \sim x_p^{-1} \cdot (1 - 1/x_p - \varepsilon/(1-x_p))^{-2} \quad (5.1-4)$$

and that of Kartvelishvili et al. (ref.43) where

$$s \cdot d\sigma/dx_p \sim x_p^\alpha \cdot (1 - x_p) \quad (5.1-5)$$

The best fitted parameters are $\varepsilon = 0.19 \pm 0.03$ with $\chi^2 = 19.2$ and $\alpha = 1.5 \pm 0.2$ with $\chi^2 = 7.2$ for 6 degrees of freedom. Our data favour the form (5.1-5). Using the fitted form of (5.1-5) to extrapolate to $x_p = 0$, $\sigma \cdot \text{Br}$ for channel (5.1-1) and (5.1-2) were evaluated to be $(23.6 \pm 2.2 \pm 4.7)$ pb and $(51.0 \pm 4.6 \pm 15.5)$ pb respectively.

The effect of $D^0-\bar{D}^0$ mixing was studied by searching for wrong sign D^0 decays from the D^{*+} channel (5.1-1), that is, the presence of D^{*+} like events in the mass combination $K^+\pi^-\pi^+$. For this study the probability cut was changed from 0.01 to 0.10 to further reduce the background from particle misidentification. An 11% upper limit for $D^0-\bar{D}^0$ mixing at 90% confidence level was obtained.

5.2 PRODUCTION AND DECAY OF THE F MESON

In searching for an F meson signal, particle identification is essential. The method used here is similar to that of the D^* meson study, with the exception that weights according to the abundance of the different particle types were introduced in calculation of the probability:

$$P_i = f_i \cdot \exp(-\chi^2_i) / \sum_j f_j \cdot \exp(-\chi^2_j/2)$$

$$i, j = \pi, K \text{ and } p$$

$$f_\pi = 5 \text{ and } f_K, f_p = 1$$

where the f_i are relative production abundances. In forming effective mass combinations, a track was used for all mass hypotheses for which this particle identification probability was greater than 5 %.

The production of $F^\pm$ mesons was obtained in the following two decay modes.

$$F \rightarrow \Phi \pi^\pm \quad (5.2-1)$$

and

$$F \rightarrow \Phi \pi^+ \pi^- \pi^\pm \quad (5.2-2)$$

As Φ candidates, all combinations of K^+K^- candidates with an invariant mass within ± 15 MeV/ c^2 of the Φ mass and with $\chi^2 \leq 16$ for the mass hypothesis were taken. Combining the two channels as independent observations, the total statistical significance of the F signal in the invariant mass distribution was 6.3 standard deviations. The mean mass was $(1973.6 \pm 2.6 \pm 3.6)$ MeV/ c^2 which agrees well with previously reported results.

The relevant angular distributions were consistent with a spin-zero assignment of the F -meson.

The scaled momentum, x_p , distribution of the F was studied and compared to the same models as in (5.1). The fits yielded $\epsilon = 0.50$ ($+0.22, -0.14$) with $\chi^2 = 2.9$ and $\alpha = 0.64$ ($+0.22, -0.20$) with $\chi^2 = 2.3$ respectively for three degrees of freedom. The distribution measured here is softer than that of D^* . This is partly explained by the ratio of the masses of the s and u or d quarks accompanying the c quark in the F and D^* mesons respectively.

The observed numbers of events were acceptance corrected and extrapolated to cover the entire x_p range using the formula (5.1-4). The following ratio of the branching ratio was obtained.

$$\text{Br}(F^\pm \rightarrow \Phi \pi^+ \pi^- \pi^\pm) / \text{Br}(F^\pm \rightarrow \Phi \pi^\pm) = 1.11 \pm 0.37 \pm 0.28$$

5.3 EVIDENCE FOR F^* MESON PRODUCTION

In analogy with the D^* meson, an excited F meson, the $J^P=1^-, I=0$ F^* meson is predicted by the quark model. Unlike the D^* meson, the F^* meson is forbidden by isospin conservation to decay strongly into $\pi^0 F$. This leaves the radiative decay as the dominant mode. We have observed a state of mass 2109 MeV/ c^2 decaying into an $F^\pm$ meson and a photon, where the $F^\pm$ meson is identified by its decay into $\Phi \pi^\pm$ as in (5.2).

In forming effective mass combination a track is entered with unity weight for each mass hypothesis for which the particle identification gives a probability larger than 3 %. The F^* signal was seen as an enhancement in the invariant mass $M(\phi\pi\gamma)$ distribution.

Evidence for the F^* production can be seen in Figure 46 on page 87, where the invariant mass $M(\phi\pi)$ for various intervals of the invariant mass $M(\phi\pi\gamma)$ are shown. There is a clear F signal correlated with a γ from the F^* interval with $M(\phi\pi\gamma) = 2.08$ to 2.17 GeV, while for the side bands there is little signal above background.

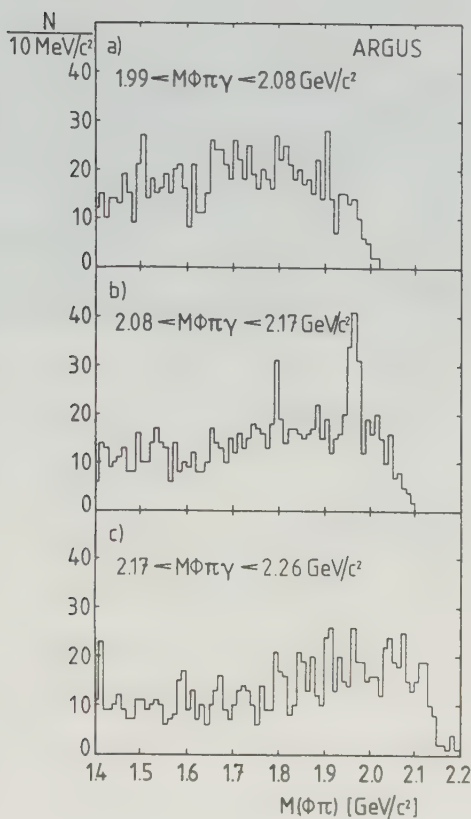


Figure 46. The invariant mass $M(\Phi\pi)$:

The invariant mass $M(\Phi\pi)$ for various intervals of the invariant mass $M(\Phi\pi\gamma)$.

6.0 SUMMARY

A study was made of particles produced in e^+e^- annihilation at a center-of-mass energy around 10 GeV using ionization loss measurements. For the first time, antideuteron production in electron-positron annihilation has been observed. The production rate in the momentum range 0.6 - 1.8 GeV/c is $[1.6 (+1.0, -0.7)] \cdot 10^{-5}$ per hadronic event. No other particles with unusual ionization have been observed. The result was converted into upper limits for the observation of free quarks, and significantly improved limits, which reach the level of 10^{-4} , have been obtained.

Also the observation and analysis of D^* , F and F^* mesons relied to large extent on the particle identification system.

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